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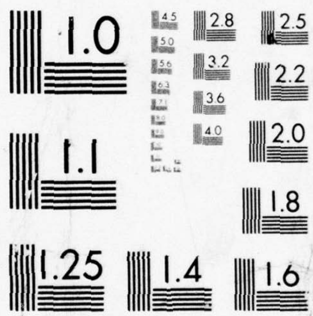

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ACTIVE ARM (EXTERNAL CARGO) STABILIZATION SYSTEM FLIGHT DEMONSTRATION

Boeing Vertol Company
A Division of The Boeing Company
Philadelphia, Pa 19142

September 1976

Final Report for Period July 1974 - April 1976

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

The results of this program substantiate the AAELSS concept as a viable approach to helicopter external load stabilization in hover, at transport speeds, and under instrument meteorological conditions (IMC).

Developmentally, the technology is now available to enable the potential AAELSS user to assess the operational benefits of the system to specific helicopters and thus to determine, through appropriate trade studies, his requirements for such a system.

Mr. Richard E. Lane, Military Operations Technology Division, was the technical monitor for this contractual program.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Development of an advanced Active Arm External Load Stabilization System (AAELSS II) for helicopters has been accomplished through analysis, ground test, and flight evaluation of the concept on a CH-47C aircraft. Hydraulically powered arms mounted beneath the helicopter automatically control load motion to provide pendular damping levels in excess of 25% of critical. The system completely eliminates longitudinal pilot-induced oscillation (PIO) over

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KEY WORDS: (Continued)

Dynamic Response
Limit Cycle
Sensor Hysteresis
Servo Control System
Actuator Stall Torque
Actuator Limit Rate
Cable Cage Follower

ABSTRACT: (Continued)

tendencies, permitting full envelope instrument meterological conditions (IMC) flight with heavy external payloads. Potential for precision hover load placement and flight with unstable loads exists. The design is also capable of operating with winchable HLH cargo hoist cable systems.

PREFACE

This report presents a synopsis of the AAELSS II development accomplished through design, fabrication, "bench" and operational ground testing, and flight evaluation of the system on a CH-47C helicopter.

The work was sponsored by the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia, and was performed by the Boeing Vertol Company, Philadelphia, Pennsylvania, under Contract DAAJ02-74-C-0063, during the period from July 1974 through April 1976.

The Army Technical Representative for the program was Mr. Richard E. Lane. Captain Richard Tarr served as U.S. Army AEFA Project Officer for flight testing at Edwards AFB, in addition to acting as the project pilot. Copilot during the flight program was CW4 John Tulloch, and the aircraft crew chief was Mr. Henry Sanford. Contributions of Army personnel to the success of the design and test programs are gratefully acknowledged.

The following Boeing Vertol personnel contributed to this program:

- Mr. W.E. Hooper - Director of Technology
- Mr. B.B. Blake - Manager, Flying Qualities Staff
- Mr. J.M. Davis - Supervisor, Helicopter Flying Qualities
- Mr. T.S. Garnett - Program Manager
- Mr. E. Kisielowski - Program Manager
- Mr. J.H. Smith - Project Engineer and System Inventor
- Mr. Y.V. Badri-Nath - Supervisor, Airframe Stress Engineering
- Mr. J.L. Hammond - Hydraulics Staff Engineer
- Mr. L. Cettel - Supervisor, Airframe Design
- Mr. F.E. Mamrol - Manager, Rotor Control Design
- Mr. T.B. Harry - Servo Systems Laboratory Engineer
- Mr. K.J. Fuller - Electrical System Staff Engineer
- Mr. B.D. Austin - Structural Test Engineer
- Mr. W.R. Hulme - Structural Test Technician
- Mr. E.D. Thornton - Offsite Manufacturing Team Leader for Edwards AFB Installation

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1.0 AAELSS II PROGRAM SUMMARY

1.1 BACKGROUND AND INTRODUCTION

External cargo missions flown with current production helicopters generally utilize some form of single-point load suspension. Because most loads with this sling configuration become dynamically unstable at speeds above 40 kn in forward flight, vehicle productivity is considerably restricted. In addition, poor inherent damping and load swinging tendencies prohibit rapid precision load placement in the low-speed/hover region.

To alleviate the problem, a dual "tandem hook" system, which employs an inverted "vee" sling attachment on either end of the load to constrain yaw motion, has been developed and tested on several CH-47 type helicopters. This load suspension approach permits operation of the aircraft to its power limits under visual flight rules (VFR).

Although the tandem hook sling load configuration reflects a substantial improvement over single-point rigging in forward flight, test pilots have noted a tendency for longitudinal PIO associated with false acceleration cues to develop when heavy loads are carried on simulated IMC cruise missions. Cases of inadvertent PIO have also been observed in VFR weather when using single-point suspension (on both single and tandem rotor helicopters), and occasionally operational pilots have been forced to jettison loads in order to maintain aircraft control.

The probability of encountering IMC related PIO goes up with increasing payload to aircraft weight ratio, and loads as light as 25% of airframe gross have caused the phenomena to occur during flight testing. Once started, PIO is difficult to stop. Extremely high levels of pilot concentration are required to arrest PIO (if it can be stopped at all) when the helicopter is being flown with flight instruments only. Because of this, IMC flight must be avoided at the present time while carrying very heavy external payloads.

Precision load placement capability in hover is less than optimal with most sling loads, and this is also true of the tandem suspension arrangement because of poor inherent damping characteristics of the load itself. Except for yaw constraint, the suspended load is essentially a simple pendulum free to swing longitudinally and laterally in response to aircraft motion. Very low critical damping ratios on the order of 0.1 or less are typical with this sling arrangement.

To realize the full performance potential of the helicopter for all weather movement of external cargo, load stability augmentation is required. In line with this need, the U.S. Army and Boeing Vertol have been developing an AAELSS concept, which involves direct control of the suspension cable attachment to the aircraft through use of powered arms mounted beneath the fuselage. An initial breadboard, "AAELSS I" device, was successfully built and tested on the Model 347 helicopter in 1972 (Reference 1). Results of this early program (sponsored by the Eustis Directorate, USAAMRDL) conclusively demonstrated the feasibility of using active arm automatic stabilization for both empty and ballasted (8,500 lb) Milvan container sling loads.

A follow-on design study (again for USAAMRDL) was undertaken in mid-1973 to improve and further develop the AAELSS concept (Reference 2). Recommendations of the study led to a third Army contract (started in July 1974) to design, fabricate, and test an "AAELSS II" system on the CH-47C helicopter (Reference 3).

This version of AAELSS has double the load-handling capacity of the original system (20,000 lb), and is mechanized to demonstrate the potential applicability of the active arm principle to an HLH-type vehicle with winchable cargo hoist cables. The system eliminates arm and cable sensor hysteresis problems encountered with AAELSS I, and is designed to provide pendular damping ratios in excess of 25% of critical. AAELSS II was flight tested in December 1975, by a joint U.S. Army/Boeing Vertol evaluation team at Edwards AFB, California. A photo of the test installation is shown in Figure 1.

The recently completed AAELSS II program consisted of five major developmental tasks:

- Design
- Fabrication and Bench Test
- Operational test on the HLH Cargo Hoist Tower
- System installation on the CH-47 Test Aircraft
- Flight Test

This report highlights AAELSS II development, emphasizing concept design implementation and flight test results.

1.2 AAELSS REQUIREMENTS

Automatic stabilization of externally slung loads is required whenever any of the following improvements in helicopter productivity is needed to accomplish the mission:

FIGURE I. AAELSS II FLIGHT TEST CONFIGURATION

- Full Envelope IMC Operation While Transporting External Cargo

  The principal AAELSS II IMC-related requirements include elimination of PIO when heavy loads are carried, and reduction in pilot workload through improved handling qualities resulting from increased load pendular damping.

- Precision Load Placement in Hover

  Low-speed AAELSS II damping requirements have been established to provide adequate attenuation of load motion in hover, and associated control laws have been developed for future compatibility with advanced aircraft precision hover hold control systems.

- Transportation of Unstable Loads

  AAELSS II active arm stabilization principles have been developed with the movement of unstable cargo as an eventual system application goal. Unstable payloads typically result when poor load aerodynamic or inertial properties combine with nonoptimum sling suspension characteristics.

Along with these general requirements aimed at upgrading helicopter productivity, the AAELSS II has also been designed to satisfy specific objectives associated with its flight evaluation on the CH-47, and to demonstrate the applicability of the HLH winch concept described earlier. Design details and flight test objectives are presented in Sections 2 and 5.

1.3 GENERAL SYSTEM DESCRIPTION AND OPERATING PRINCIPLES

Figure 2 illustrates the functional arrangment of the major AAELSS II mechanical components, and the schematic drawings in Figure 3 detail various supporting hydraulic, electrical, and cargo hook subsystems. Starting at the top of Figure 2, basic AAELSS elements include two 5-foot articulated arms, arranged in tandem on the fuselage bottom and located 12 feet apart. Both arms are hydraulically powered by individual longitudinal and lateral servo actuator cylinders, and these are driven by the aircraft utility hydraulic system. Each arm is attached to the airframe through a pivot and pillow block assembly, which permits ±50 degrees of longitudinal motion and ±30 degrees of lateral travel. Structural loads generated by the arms are transferred directly into the fuselage frames and skin through rigid external steel attachment frames that distribute the loads uniformly.

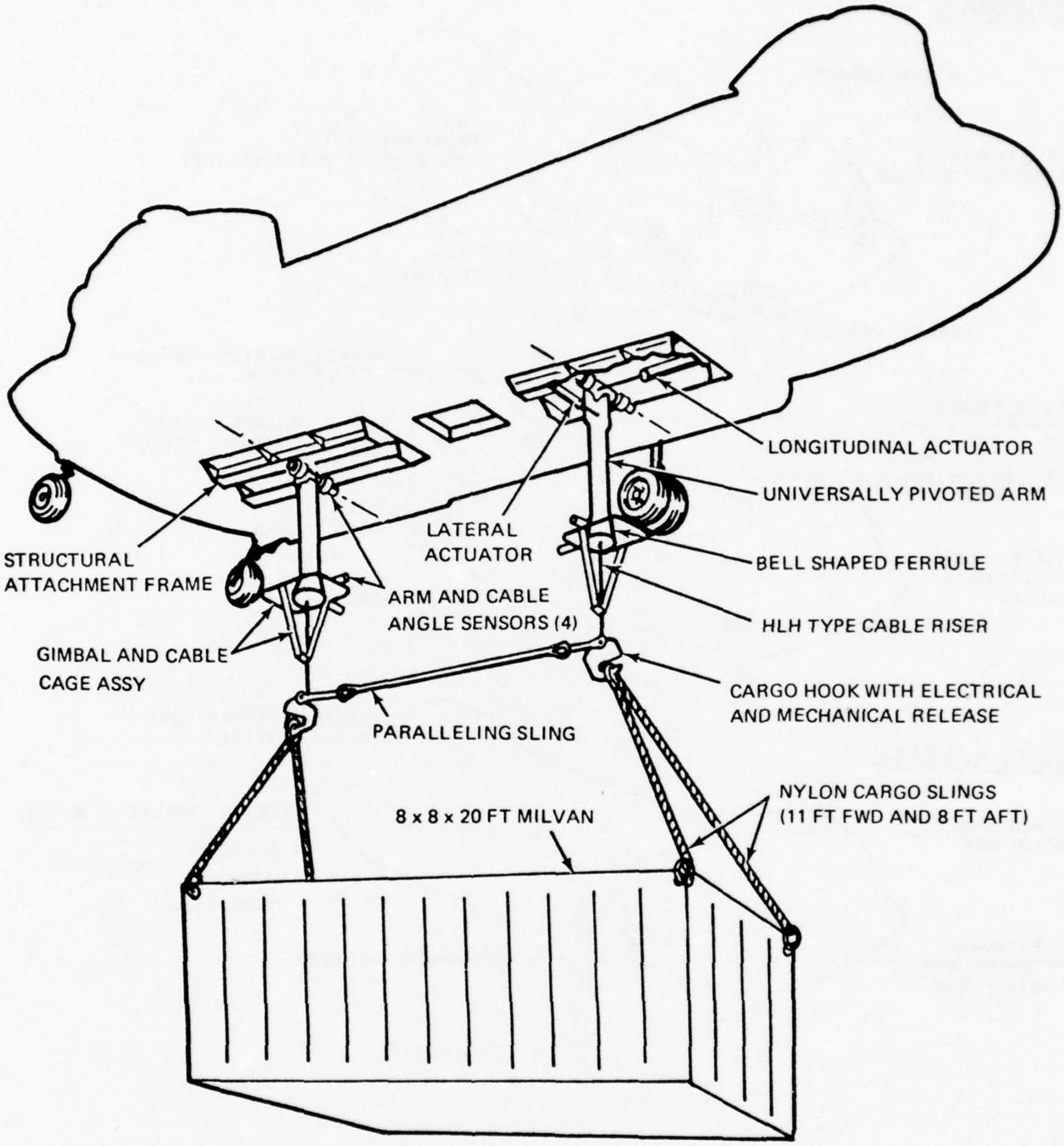


FIGURE 2. ACTIVE ARM EXTERNAL LOAD STABILIZATION SYSTEM (AAELSS II) TEST INSTALLATION

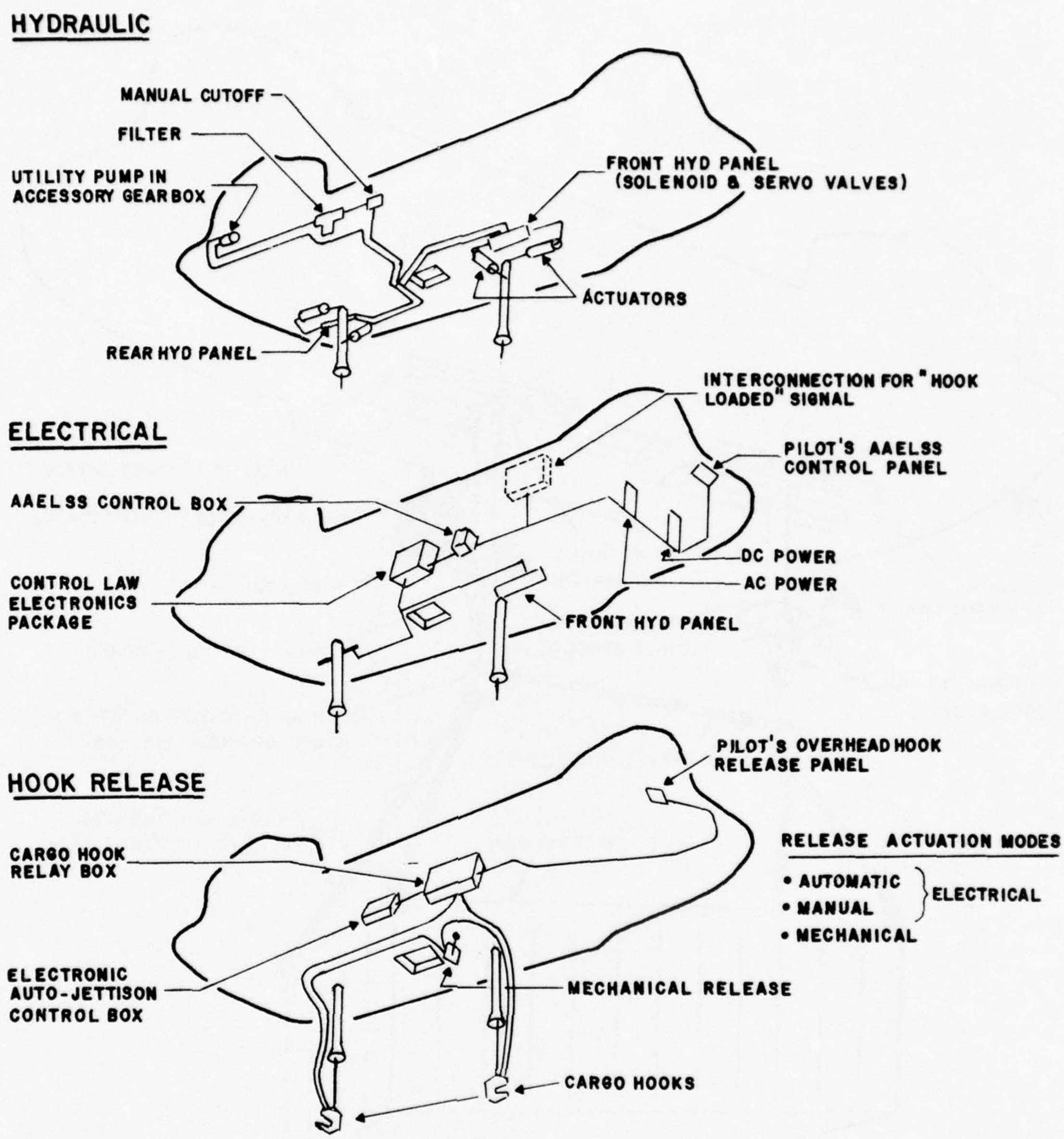


FIGURE 3. AAELSS II TEST INSTALLATION SUBSYSTEMS

The central tension member in the AAELSS II load suspension scheme is a 9-foot section of flexible HLH cargo hoist cable. Pinned at its top, the cable passes down the hollow rigid arm and out the bottom through a flared guidance ferrule installed to prevent cable wear due to bending or kinking. Gimballed about this ferrule is a cable cage follower assembly that facilitates measurement of cable angles relative to arm position. Synchro packages mounted on the cage follower and at the top of the arm constitute the source of angular feedback information utilized by the automatic control laws.

At the bottom of each cable is a cargo hook connecting the suspension riser to a set of conventional dual nylon cargo slings supporting either end of the load. A paralleling sling ties the two hooks together to prevent them from rotating. When the system is operating, AAELSS hardware is deployed as shown in Figure 2, but the arms are automatically retracted and the hooks are reefed inside the fuselage during takeoff and landing maneuvers.

AAELSS stabilization principles are relatively simple, and the uncomplicated control laws involved are not an integral part of the normal aircraft stability augmentation system. The load pendular motion is damped by operating both arms in the same direction to stop longitudinal and lateral sway, and in opposite directions (laterally) to attenuate yaw. An illustrative example of how the system works is given in Figure 4.

At the top of the figure is a series of "cartoons" representing the arm, the cable (relative to arm), and the load pendulum motion, before and after the AAELSS is engaged. The length of the velocity vector indicates relative magnitude of the arm and load motion. On the left, the load is depicted in its free-swinging mode operating as a simple pendulum with AAELSS off. This lightly damped oscillation (with the critical damping ratio ζ typically <0.1) at A is assumed to have been excited by aircraft motion, gusts or some other disturbance.

When the system is engaged, the arm is commanded in the same direction as the load, but delayed by simple lag/washout control shaping (described later). The net effect is that the arm moves to retard the load pendular motion as shown at B, C, and D. Load excursions subside rapidly after AAELSS activation, with typical damping levels of approximately 25 to 30% of critical measured in flight test. Without AAELSS, load motion tends to persist for a very long time with an attendant adverse effect on handling qualities.

1.4 SYSTEM DESIGN

Preliminary design of the AAELSS II system was accomplished in the Reference 2 study, but two significant departures in the

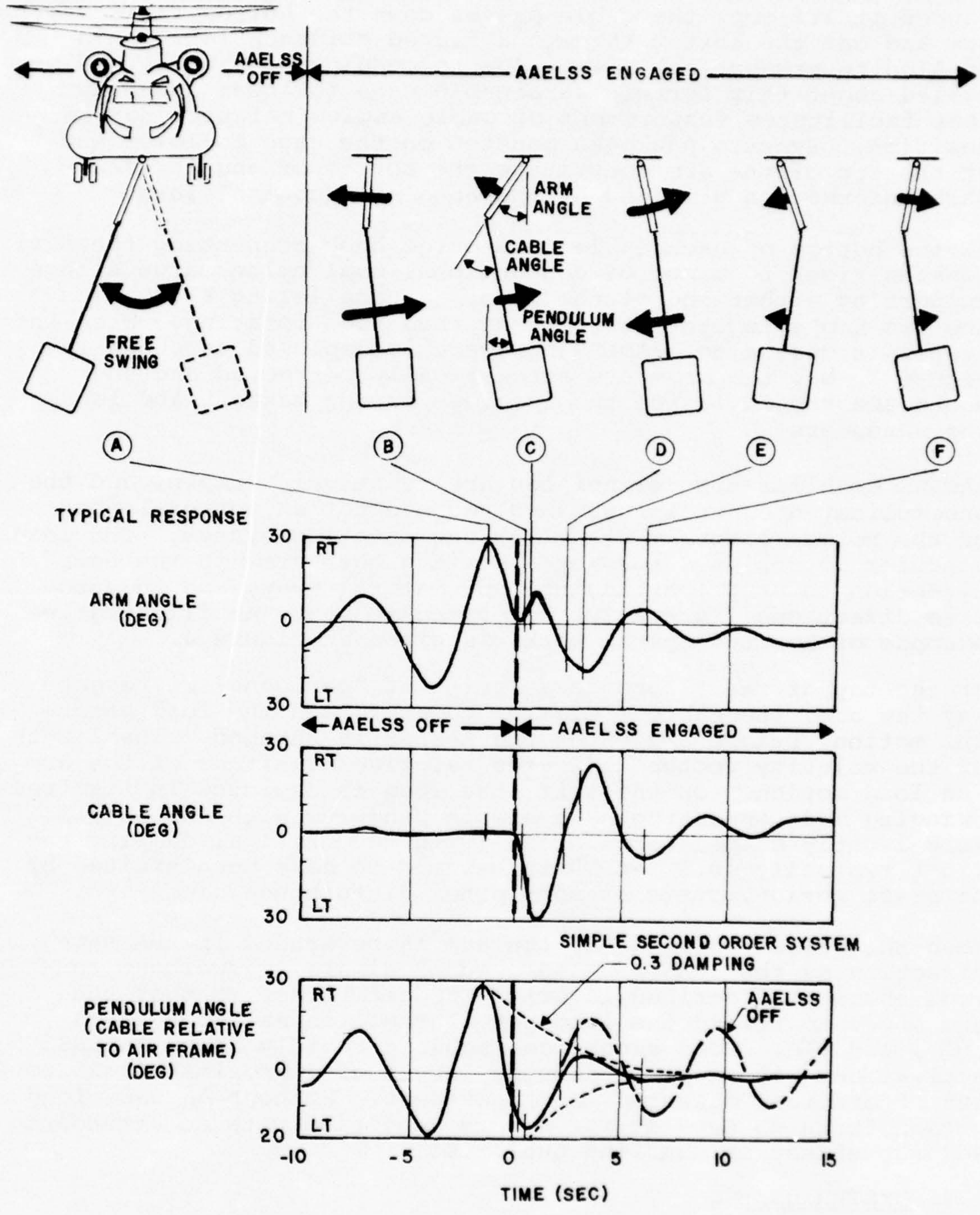


FIGURE 4. AAELSS II STABILIZATION PRINCIPLES

area of hardware mechanization were required during adaptation of the concept for CH-47C flight demonstration. These changes included:

- Application of Teflon-lined bearing technology (instead of needled bearings), to better handle oscillating loads imposed on arm and actuator mounting hardware

- Revision of the arm/fuselage interfacing concept from one requiring complicated "beef up" of internal aircraft structure, to another using a simple externally mounted box beam load distribution framework with no internal airframe modification whatsoever.

These two design modifications substantially simplified and improved the AAELSS II flight test installation, and both performed well throughout the program. Other design features unique to AAELSS II contributed to the successful flight demonstration as well. Among these were the HLH winch compatibility features, including the cable tension member, ferrule, and the cable cage and arm sensor system which eliminated hysteresis problems identified in AAELSS I.

A brief summary of the final design criteria to which AAELSS II was built is presented next. Following this summary is an assessment of the design approach utilized in developing the servo arm drive and control law packages that form the heart of the AAELSS II system.

1.4.1 Design Criteria

Specific criteria adhered to in design of the AAELSS II flight demonstration system are divided into four general categories:

HANDLING QUALITIES AND ELECTRICAL SYSTEM

- The AAELSS II system is designed to provide minimum pendular damping levels of at least 25% of critical for all flight conditions.

- Because of the experimental nature of the test installation, redundancy in system electronics is not provided. Accordingly, the flight demonstration envelope is governed by recovery from potential system hardover and go-dead situations.

- Cable and arm angle sensor installations are configured to prevent undesirable hysteresis effects observed in AAELSS I.

- Both axes of each arm are provided with separate control law packages to prevent cross coupled failure modes, etc.

- System control law shaping parameters are fully adjustable in flight to facilitate AAELSS optimization.

- AAELSS operation is disabled when the cargo hooks are unloaded to protect ground crewmen during load hookup.

- Separate control panels are provided for the pilot and system evaluation engineer, with hook "load status" information available for the pilot. Automatic arm retraction can be initiated from either crew station.

STRUCTURES

- AAELSS II structure is designed for normal full envelope operation with payloads up to 20,000 lb. Design loads are dictated by an assumed single failure of a cable riser, hook, or sling suspension, followed by payload swing and subsequent retention of the load by the remaining arm.

- Design fatigue life of the test installation is 50 hours (7,200 operating cycles), which is approximately four times the anticipated length of the flight program.

HYDRAULICS

- Hydraulic cylinder load capacity is sized to eliminate undesirable actuator stalls of the type encountered in AAELSS I. Design stall torque of approximately twice AAELSS I performance is required. The final 11,800 ft-lb AAELSS II maximum torque capacity exceeded this goal by 20%.

- AAELSS II hydraulic power requirements are deliberately minimized to reduce aircraft utility hydraulic system loading. Actuator maximum flow rates of approximately 2 gpm (with accumulator backup for peak operation) are provided. AAELSS I actuators required up to 5 gpm flow.

- An interfacing system connecting individual AAELSS units to the aircraft utility supply is installed with its own filter and manual safety shutoff.

CARGO HOOK SYSTEM

- The SRD-84 cargo hook system as described in References 4 and 5 is a safety feature of the tandem hook suspension and is incorporated in the AAELSS II design. It has three operating modes: manual, automatic, and emergency. Manual (electrical) hook release is provided for the pilot, copilot, and crew chief for low speed flight. Above 60 kn, an "auto jettison" feature releases the load automatically if either hook or suspension system fails. Emergency electrical jettison is possible at any time.

- A "backup" mechanical emergency release system operated by the flight engineer/observer is also incorporated for added safety.

- Eastern Rotorcraft (C-250) cargo hooks capable of releasing under 30,000 lb loads are utilized with the system.

1.4.2 Design Approach

ARM SERVO DRIVE MECHANIZATION AND CONTROL LAWS

Servo Drive - Figures 5 and 6 illustrate how the active arm stabilization principles introduced earlier are actually applied in the AAELSS II mechanization. Combined servo actuator drive and control law schemes are discussed first, followed by a synopsis of the design analysis carried out to establish parameter sizing, etc, shown in Figure 7.

Essential elements in the arm drive and feedback control system are depicted in Figure 5. Only one axis is shown, but all four arm actuators operate the same. On the right are the actuator and its servo valve control elements, and on the left, the arm and cable suspension with associated synchro sensor feedbacks. Control shaping is at the top.

The system operates by sensing the angle that the cables make with respect to the arm, and the arm angle relative to the airframe. These are summed to form the "pendulum angle," which describes the payload force line of action with respect to the fuselage. Pendulum angle signals are passed through the control shaping network, detailed in Figure 6, to produce the desired load damping commands for the position servo amplifier and electrohydraulic valve (EHV).

Activation of hydraulic fluid flow into the EHV is controlled by a solenoid shutoff valve, which the pilot energizes with a switch. When the solenoid valve is open, flow (at C) passes directly into the EHV and downward to (B), forcing the bypass valve spool to the left to open up channels (C_1 and C_2) between the actuator piston and the EHV. Servo amplifier commands control the EHV spool (not shown) to permit flow into the C_1 channel and out of the C_2 passage, or vice versa.

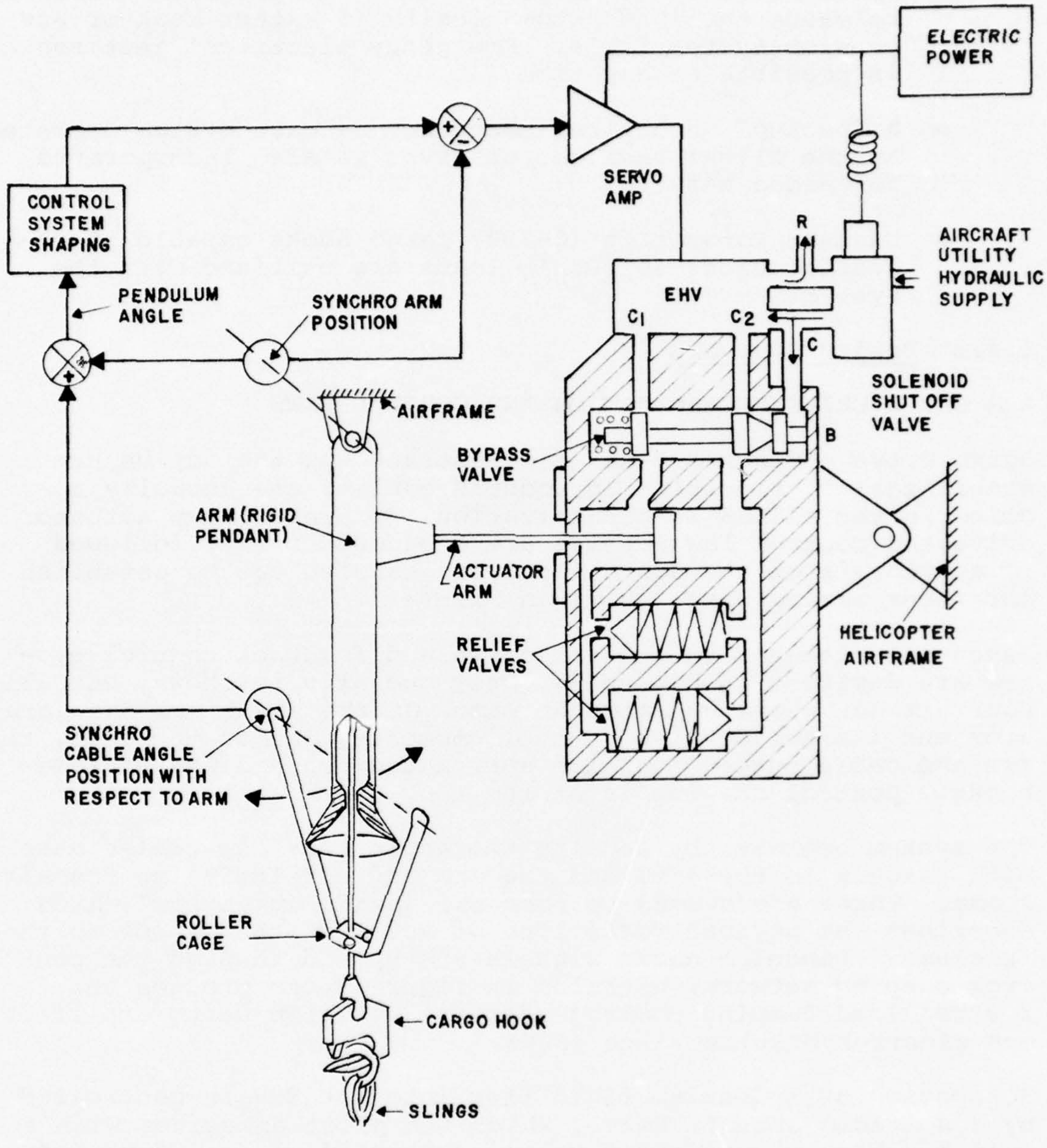


FIGURE 5. TYPICAL ARM SERVO DRIVE, SINGLE-AXIS AAELSS

NOMINAL CONTROL LAW PARAMETER SETTINGS				
SLING	AXIS	K-GAIN $\frac{\text{DEG ARM.}}{\text{DEG PEN.}}$	τ LAG - SEC	τ_{WO}-SEC
37 FT RISER	LONG	20.0	3.3	15.0
	LAT	15.0	3.6	3.0
STANDARD	LONG	10.0	2.3	15.0
	LAT	7.5	2.8	3.0

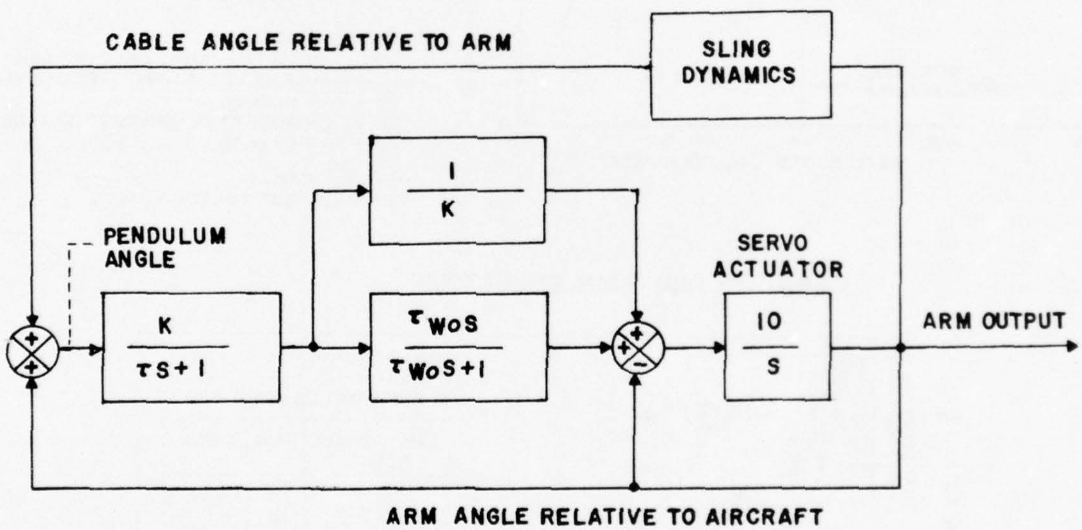
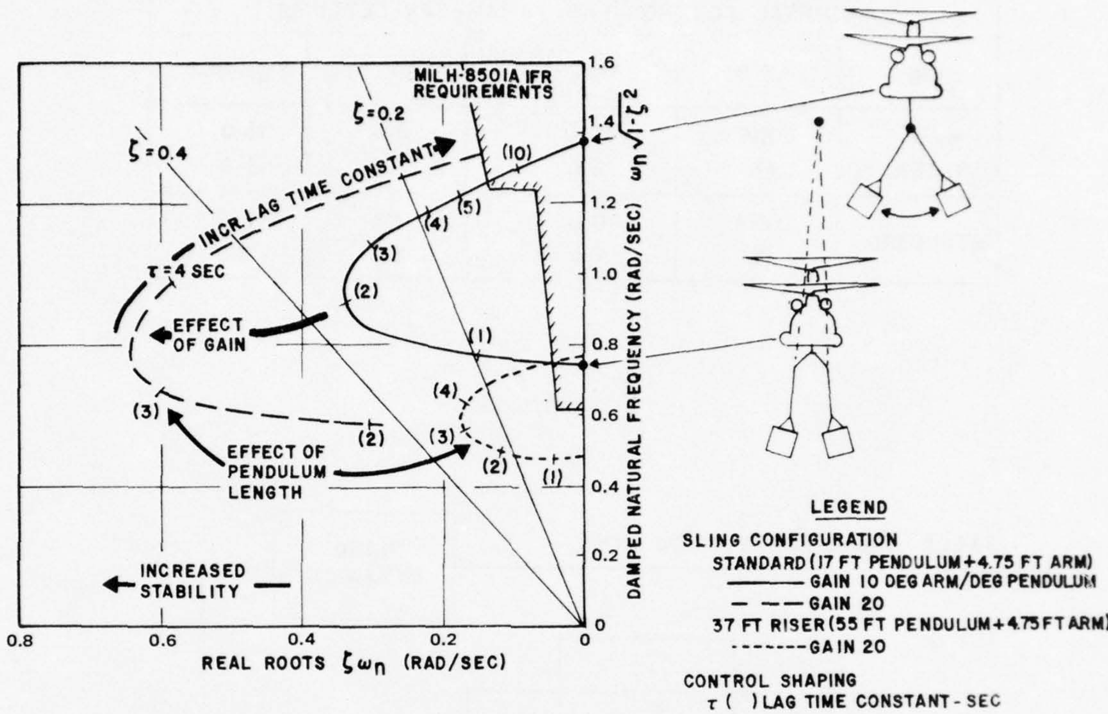


FIGURE 6. CONTROL LAW BLOCK DIAGRAM

CONTROL LAW ROOT PLACEMENT IN HOVER



CAPACITY AND GAIN SELECTION

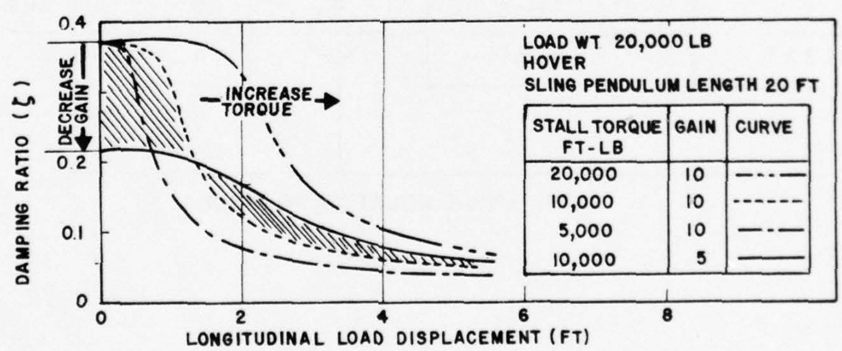


FIGURE 7. AAELSS II DESIGN ANALYSIS

In this manner, actuator arm motion is produced in either direction commanded.

The lower relief valves prevent hydraulic lock when the arm is being overpowered by load motion. In the position shown with the solenoid valve shut off, fluid is permitted to circulate below the bypass valve, allowing unrestricted freedom of arm motion.

Control Law Development - Control law shaping adopted for AAELSS II consists of a simple lag/washout combination, which provides the required damping and return to trim characteristics desired. Figure 6 shows this shaping network along with a summary of optimum gain and time-constant parameter settings established during the flight program. The feed-forward path around the washout is employed in the longitudinal axes only. It compensates for steady pendulum trail angles encountered when aerodynamic drag in forward flight forces the load to trim in an aft position as seen in Figure 1.

A number of candidate control law possibilities were investigated in the AAELSS I and AAELSS II preliminary design phases, but the lag/washout approach proved to be the most effective overall. Among the controllers evaluated for the original system were several networks employing higher order transfer functions, and operating on the cable rather than pendulum angle relationships. The stability of these systems was very sensitive to gain level, as was the case with angle rate controller systems, which were also investigated for AAELSS II.

Typical methodology applied in parameter selection and sizing for AAELSS II control laws is displayed in the Figure 7 root locus and capacity requirement plots. Analysis of the theoretical root placement and/or time-history evaluations were utilized as primary tools in the AAELSS stability design evaluation. Root progression plots for the major pendulum modes illustrate the effects of varying the sling suspension length, and the control law time constants and gains. The reduced levels of stability and lowered frequencies characteristic of the longer sling configuration are obvious from the plot.

Stability roots for the short sling configuration are shown at the top of the plot with variations in lag time constant from zero to infinity indicated. Very high time constants force the arm to become rigid as indicated in the upper sketch. As the lag is reduced toward zero, arm action becomes "sharper" until the overall system behaves like the "elongated" free-swinging pendulum at the bottom. Selection of time constants between these extremes, and in the range of 2.5 and 3.5 seconds, proved to be optimum during the flight program as would be surmised from the theoretical predictions. It is interesting to note that the final damping performance with AAELSS on exceeds MILSPEC H8501A requirements for IMC flight by a factor of about six for both sling configurations in hover.

Increasing the gain level improves load damping generally, but a compromise must be made when selecting maximum values for use on the aircraft. As seen in the lower Figure 7 plot, once the actuator stall torque capacity has been established, the selection of a system gain will then depend upon whether high levels of damping are desired over a narrow band of load motion (requiring high gain settings), or if a wide range of motion with lower damping is preferable. In the cross hatched example shown, when maximum damping is required for load excursions in excess of 1.5 ft, the lower gain setting (of 5 deg/deg) is the best overall compromise. Note that the 10,000 ft-lb stall torque selected in the example is close to the sizing required for AAELSS II. This capacity is essentially the maximum available without overtaxing the aircraft utility hydraulic system.

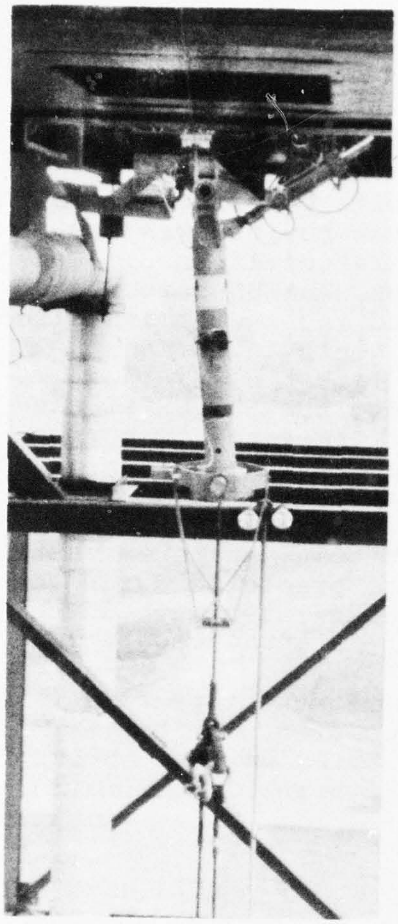
1.5 "BENCH" QUALIFICATION TEST

After fabrication, a single AAELSS arm assembly underwent "bench" qualification structural testing on the HLH cargo handling tower (Figure 8). Objectives of this test were to qualify the system for anticipated steady and alternating flight loads, and to evaluate "critical component" wear characteristics. Critical components identified at the onset of AAELSS II development were the cable tension member, ferrule, and Teflon-lined bearings supporting the arm and actuators. Additional testing included evaluation of the automatic arm retraction sequence.

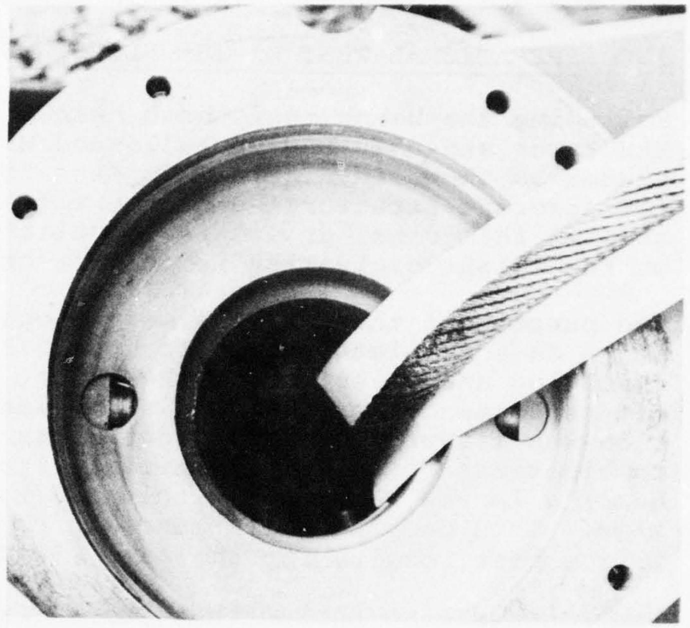
Test loads included a concentrated 12,000-lb weight, representing an assumed maximum 60:40 split in arm load distribution for the 20,000-lb design condition. Testing consisted of driving the arm sinusoidially to its stall torque amplitude through use of a signal generator commanding the lateral and longitudinal actuators; first in one axis, then in the other, and finally with both operating together. Thirty-nine hours of testing produced 22,200 cycles of the cable, and 16,400 actuator cycles. After completion of this test, the cable was successfully proof-loaded to 60,000 lb.

"Critical Component" test results were very satisfactory as shown in Figure 8, with negligible cable wear noted and only minor polishing of the ferrule visible. Teflon bearing surfaces examined after disassembly were also in excellent shape.

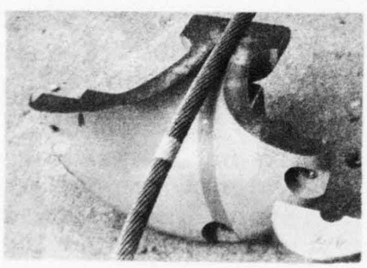
During the test, the lateral actuator arm attachment lug failed because of poor weld penetration in the joint. The problem



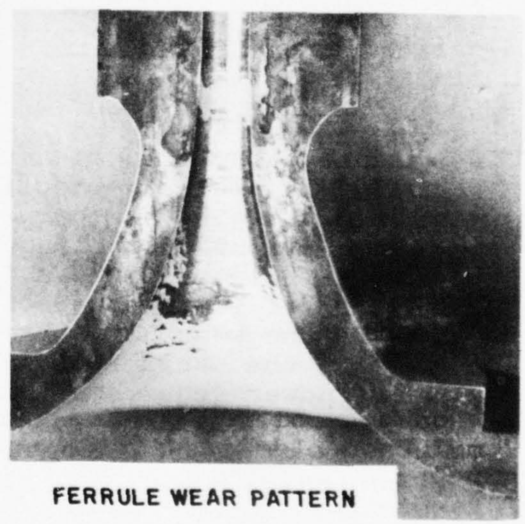
INSTALLATION ON TOWER



LOWER ARM WITH FERRULE REMOVED
SHOWING CABLE



DISASSEMBLED FERRULE
& CABLE



FERRULE WEAR PATTERN

FIGURE 8. AAELSS II CRITICAL COMPONENT WEAR FOR 22,000 CYCLE BENCH TEST

was corrected on the flight test AAELSS units by adding a canted doubler to each lug, which provided additional weldment surface and reduced stress loads appreciably.

1.6 OPERATIONAL TEST OF THE FLIGHTWORTHY SYSTEM

Following the bench test, both AAELSS units were mounted on the HLH tower and a 20,000-lb ballasted Milvan payload was suspended as shown in Figure 9 for the "operational" test. Except for aircraft structural attachment frames, AAELSS components used in this final ground test duplicated the system installed on the flight evaluation helicopter one month later.

The purpose of this testing was to operate the AAELSS II elements as a complete system for the first time, and to correct resulting anomalies before the flight test. In addition, damping performance for the long sling load (37-ft riser) configuration was measured while using various gain and lag time constant combinations to establish initial flight test parameter settings. Damping levels were well within the range predicted during design. This damping performance is compared later with actual flight test results for the same sling load arrangement.

Tower tests also showed that the AAELSS II sensor package eliminated limit cycle oscillations associated with hysteresis in the earlier system. In winds gusting to 25 kn, the AAELSS II was shown to hold load position within ±1.5 in. longitudinally and ±3.0 in. laterally.

1.7 FLIGHT TEST EVALUATION

1.7.1 Synopsis

The recently completed 14-hr AAELSS II flight evaluation met virtually all pretest objectives, including demonstration of pendular damping levels between 25 and 30% of critical, and complete elimination of longitudinal PIO under simulated IMC conditions while carrying a 15,000-lb Milvan container at the aircraft power limit speed of 105 kn. AAELSS II was shown to be free of the sensor hysteresis and actuator stall problems observed in the earlier AAELSS program, and did not impose excessive power requirements or unsafe conditions on the test aircraft. The system successfully demonstrated applicability of the concept to an HLH-type helicopter with winchable cargo hoist cables.

Although AAELSS II eliminated nearly all AAELSS I deficiencies, a long period lateral axis oscillation appeared randomly on the front arm in forward flight. Traced to a hardware malfunction, this problem was not completely solved during the

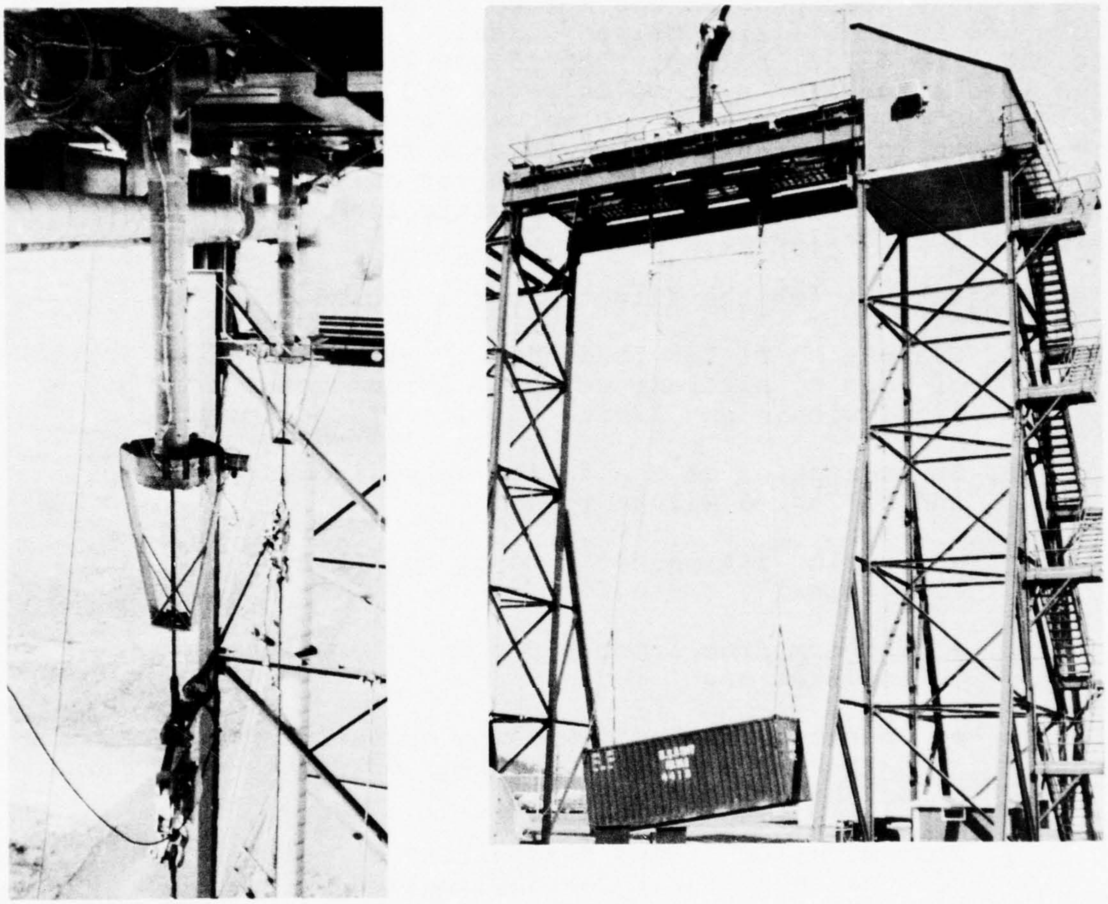


FIGURE 9. OPERATIONAL TEST ON HLH CARGO HANDLING TOWER

short two-week test program. Analysis indicates that a minor modification of control law feedback shaping will reduce the system's susceptibility to hardware faults of this nature.

1.7.2 Flight Test Scope and Objectives

The Edwards test program was set up to evaluate AAELSS II performance in stabilizing Milvan container loads ranging in weight from 4,700 lb (empty) to 15,000 lb, while using short and long suspension systems in hover and forward flight. The "standard" short sling (11 ft forward and 8 ft aft) arrangement shown in Figures 1 and 2 was used for most testing, but a 37-foot riser was inserted (for hover only) between hook and sling attachment points to simulate load winching operations with a ballasted Milvan.

Test objectives for the flight program included:

1. Evaluation of longitudinal PIO with significant ratio of load to airframe weight (maximum considered practical within the limits of aircraft performance).

2. Demonstration of the following while carrying empty and ballasted Milvan loads:

   - Damping ratios equal to or better than AAELSS I (typically $\zeta \leq 0.25$)

   - Freedom from limit cycle or other lightly damped oscillations

   - Operation without imposing excessive power requirements on aircraft subsystems or unsafe conditions on the helicopter

3. Demonstration of the feasibility of using AAELSS II components suitable for application with an HLH type winchable cable, including arm, ferrule, and cable tension member along with conventional fixed cargo slings.

4. Exploration of dynamic stability conditions not investigated in the AAELSS I tests, including operation with a single-arm axis inoperative.

1.7.3 Test Procedure and Conditions

All AAELSS II flight testing was based on the aircraft having at least out-of-ground-effect (OGE) multiengine hover capability with the load on the hooks. Added to this OGE requirement was a small additional torque margin for vertical maneuvering to arrest inertial load motion. Potential single-engine emergency situations in hover required immediate load jettison, and then sufficient in-ground-effect (IGE) performance on the remaining engine to stay well above the load.

Prior to flight testing, the aircraft was rolled over a large pit and the AAELSS arms were deployed. Complete checkout of all systems was accomplished, including both electrical and mechanical hook jettison functions, and operation of AAELSS itself. Before each flight, the arms were exercised over the pit to reduce the probability of unexpected in-flight malfunction.

Initial instrumentation and functional checkout flights verified proper operation of the AAELSS and SRD-84 hook systems, using concentrated single-point loads varying in weight from 700 to 1,200 lb on both hooks. Flight testing with the Milvan typically was started in hover and then progressed into forward flight, employing normal buildup techniques to ensure safety.

In the hover phase, AAELSS control shaping time constants and gain settings were varied to determine which produced the best damping and pilot handling qualities rating (HQR) scores. With the optimum parameters selected in hover, forward flight data points were set up where the following items were evaluated at each airspeed, and in the order listed:

- <u>AAELSS off baseline</u> sling load <u>damping</u> response to aircraft excitations (in the longitudinal, lateral, and directional axes) at the load natural frequency was checked first. At no time was testing "continued beyond the point at which the load began to display unstable characteristics. This procedure was followed to ensure the existence of stable load conditions in the event that one or more AAELSS axes failed inadvertently during subsequent "AAELSS on" testing.

- <u>Aircraft/load response</u> to simulated <u>AAELSS hardover</u> and go-dead situations was assessed after "AAELSS off" testing. Single-axis, single-arm operation was also evaluated from the standpoint of stability and safety.

- <u>AAELSS on damping wa</u>s determined next; with the system off initially during the aircraft excitation, and then on. HQR assessments for these dynamic stability runs were made with the <u>pilot in the loop</u> as AAELSS damped the load, and with the pilot completely out of the loop for recovery. Dynamic stability testing was followed by a series of typical mission-oriented maneuvers, including turns, precision load shuttle/placement tasks, and lift-off with offset loads. Where practical, maneuvers were evaluated with AAELSS off first, and then with AAELSS on augmentation assisting the pilot.

- Longitudinal PIO susceptibility was evaluated with AAELSS off, then on, while flying under simulated IMC conditions (pilot under the hood).

Ten flights were conducted during the program, with the first two devoted to system and instrumentation functional checkout. Three flights were related to long riser/heavy load (11,800 lb) testing in hover. Single flights were flown for each of the heavy and light short sling configurations in hover. Two flights were flown with the standard short sling/heavy load in forward flight that reached 100 kn maximum speed. An additional flight to 80 kn picked up the same conditions for the empty Milvan in cruising flight. A final maximum performance flight with a 15,000-lb Milvan was devoted to PIO investigation and high-speed load dynamic stability evaluations.

Two hundred eighty-eight data points were recorded during this program, of which 236 were directly related to AAELSS performance assessments.

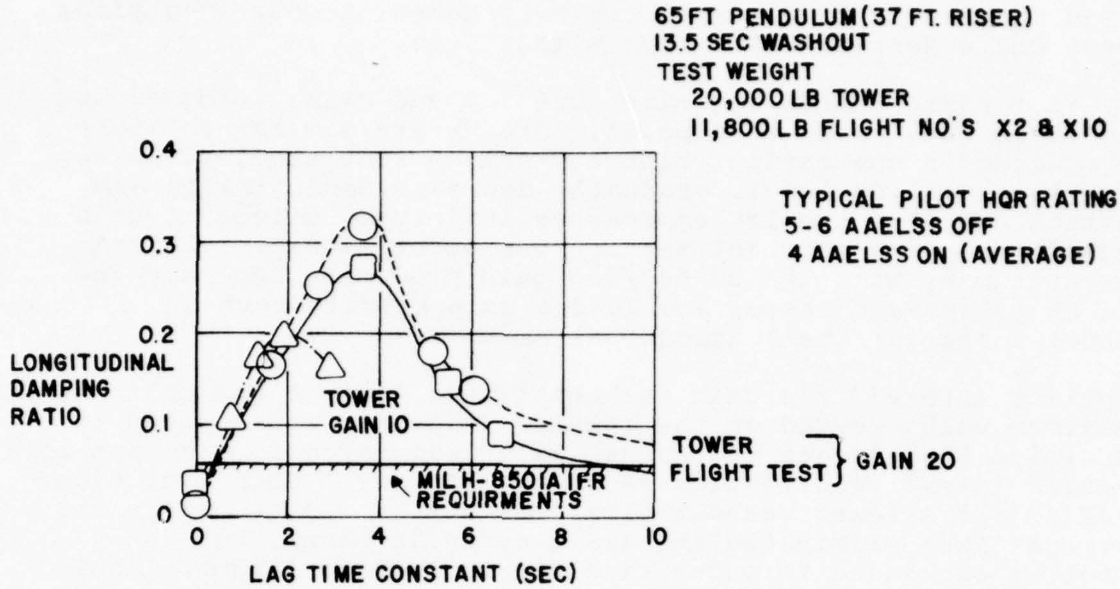
1.7.4 Test Results

Principal results of the flight program are summarized in Figures 10, 11, 12, and 13. The first two of these cover damping and associated pilot HQR ratings, and the final plots illustrate significant time history information such as the heavy load PIO demonstration.

Discussions of test results are presented so each sling and payload combination is highlighted separately. Heavy box/long riser hover testing is described first, followed by results for the short sling (heavy and light) configurations in hover. Forward flight is reviewed last.

LONG RISER/HEAVY PAYLOAD - HOVER

As indicated earlier, HLH tower tests preceding the flight program utilized a setup approximating conditions that would exist with the AAELSS installed on a perfectly stable helicopter (at the start or finish of winch operations). Combinations of six longitudinal and five to eight lateral axis lag time constants were evaluated (along with two different gain levels) to optimize performance. In the Edwards CH-47C test, similar parameter variations were flown with 10,000 and 11,800 lb payloads. Flight and tower test results are compared in Figure 10.



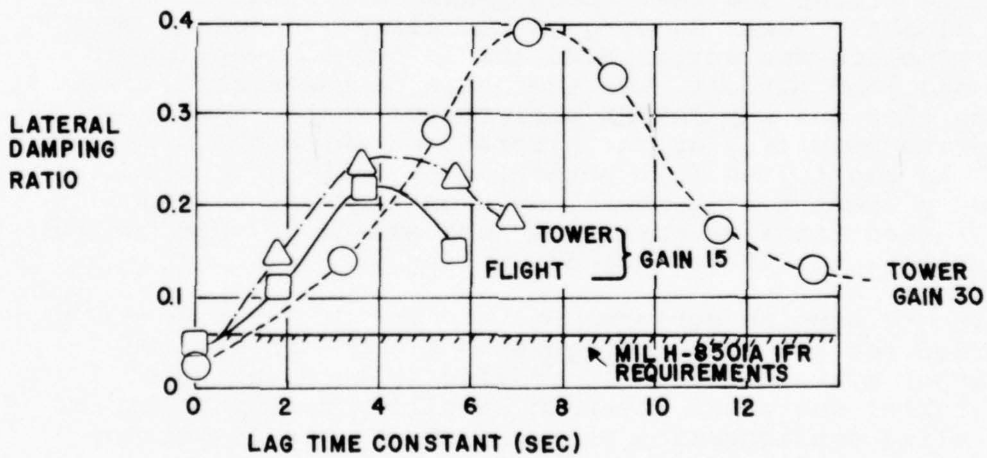


FIGURE 10. COMPARISON OF AAELSS II DAMPING IN HOVER TOWER VS FLIGHT TEST (LONG RISER)

Damping for the longitudinal axis is depicted at the top of the plot, and lateral axis data at the bottom. AAELSS-off basic sling load performance is indicated where the damping curves intersect the vertical axis. Note that inherent sling load damping is quite low (generally $\zeta < 0.05$). This lack of load damping in hover is the primary cause of poor load placement characteristics for most sling loads.

By increasing AAELSS lag time constant and gain, load damping improves rapidly up to a point. Trends are similar to those predicted in the earlier Figure 7 design root studies. After peaking, damping levels gradually decrease, and finally arm action stops as the lag approaches infinity. Effect of gain on optimum time constant setting was about as expected from predictions, with the 20-deg/deg gain producing best damping in the 3-1/2-sec range, and 10-deg gain results best at about 2 sec for the longitudinal axis.

Optimum lateral axis gain for the flight vehicle was half the maximum value tested on the tower. This gain was reduced to minimize the effects of the hardware-associated forward arm long period lateral oscillation described earlier. Gain reduction, and use of a lower washout time constant (τ = 3.0 sec) in the lateral axis eliminated the limit cycle in hover, but the problem continued to occur randomly in forward flight. Analysis indicates that minor modification of the lateral control laws would solve the problem.

In comparing flight and tower test AAELSS performance, Figure 10 shows slightly lower damping on the flight vehicle. This damping reduction was anticipated and is due to coupling of aircraft and load motions. On the basis of these results, it is obvious that one way AAELSS performance can be maximized is to improve stability of the aircraft on which the system is used. In short, the full potential of AAELSS for precision hover load placement is best achieved on aircraft with good low speed/hover handling qualities such as the 347-HLH control system demonstrator (Reference 6).

In addition to damping performance, a pilot qualitative HQR was recorded for all test configurations. The well-known Cooper-Harper system of 1 to 10 scoring (with a rating of 1 most desirable) was used. Dynamic stability test results for the long sling configuration produced HQR scores of between 5 and 6 for the basic sling load. Ratings improved to an average of about 4 with AAELSS engaged. The long sling maneuvers generated the lowest HQR scores of the test program, but these improved along with damping when the standard sling suspension was installed for the remainder of the program.

STANDARD SHORT SLING HEAVY AND LIGHT PAYLOAD - HOVER

Typical damping performances for the various hover configurations are compared in the Figure 11 bar chart. As shown on the right, reducing sling length by removing the 37-foot riser improves AAELSS on damping about one-third longitudinally and three-quarters laterally, with an attendant increase in pilot HQR rating of approximately one point. Damping levels reflecting the higher inherent load stability characteristics of the shorter suspension averaged between 0.25 and 0.30 at optimum lag setting. Parametric variation of lag shaping to determine best damping performance produced the same trends observed with the longer sling, but the peaks occurred at a lower time constant.

In the center of the chart, AAELSS short sling damping contributions are shown to be insensitive to gross weight effects for empty and ballasted Milvan payloads. Both cases display test measured damping two and one-half to three times that of the MILSPEC IMC requirement.

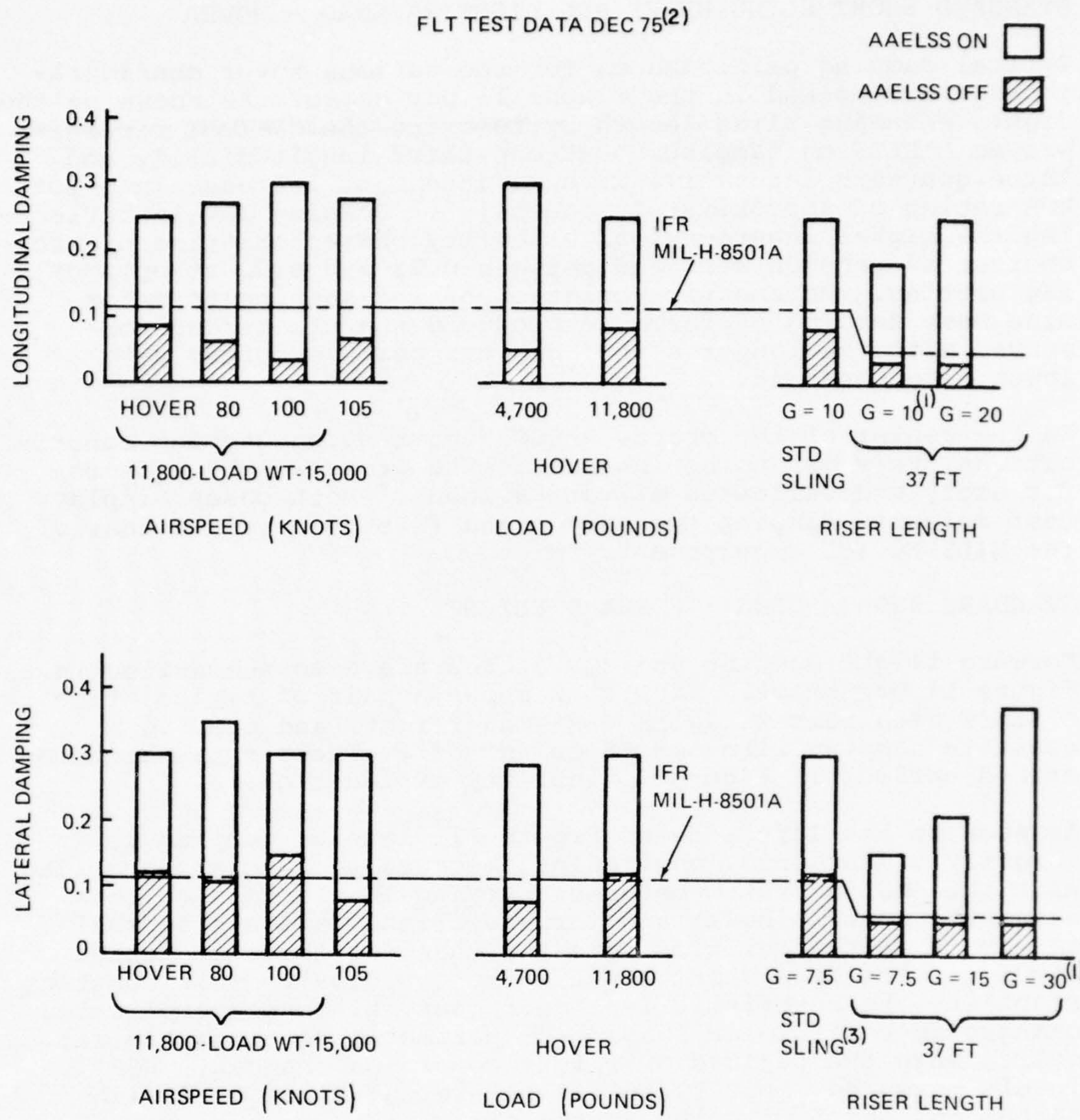
STANDARD SHORT SLING - FORWARD FLIGHT

Forward flight damping and HQR scores are also summarized in the Figure 11 bar chart. Figure 12 shows a pair of typical time history data runs taken in cruising flight, and used to evaluate damping with AAELSS on and off. These runs were described earlier in Figure 4, stability explanation.

As seen on the left side of Figure 11, lateral damping is slightly higher than longitudinal because of aircraft coupling. With the AAELSS system engaged, damping levels tend to be about the same in hover and forward flight, and are approximately three to four times greater than for the unaugmented load (varying from about $\zeta = 0.25$ to $\zeta = 0.39$). This constant stability characteristic is significant, since no complicated changes in control law shaping or parameter settings are required when the payload or flight condition changes. HQR levels measured in forward flight average close to 3 with AAELSS on, and 5 with the system off.

Single-axis operation was stable for all cases evaluated including high-speed flight with the empty Milvan, but damping levels were reduced as expected. Because of this generally favorable performance, some potential exists for mechanizing a simplified single-arm AAELSS system to meet the PIO associated cruise IMC requirements delineated earlier.

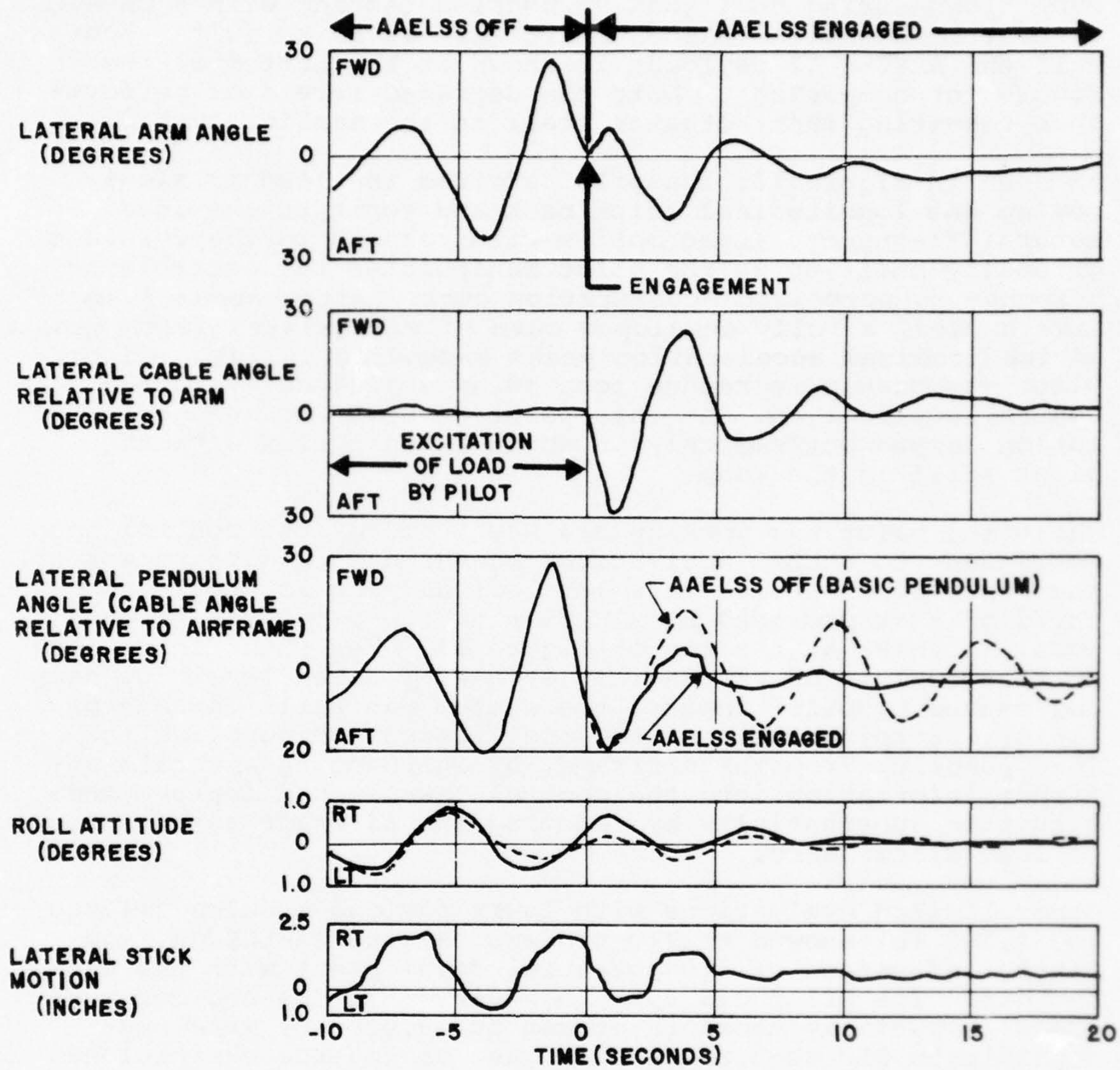
PIO RECOVERY - The most significant piece of test data recorded during the entire AAELSS II flight program is presented in the PIO time history at the top of Figure 13. This maneuver was flown under simulated IMC flight with a 15,000-



TYPICAL HQR RATING STANDARD SLING		
	AAELSS OFF	AAELSS ON
HOVER	5-6	3-4
FWD FLT	4-5	3

G CONTROLLER GAIN – DEG ARM/DEG CABLE
(1) HLH TOWER OPERATIONAL TEST
(2) CH-47C SN 15858 @ EAFB, CALIF WITH 8x8x20 FT MILVAN
(3) 11 FT FWD AND 8 FT AFT SLING – NO RISER

FIGURE 11. AAELSS II DAMPING AND HANDLING QUALITIES RATING SUMMARY



HELICOPTER GROSS WEIGHT 36,928 LB
EXTERNAL LOAD GROSS WEIGHT 4700 LB
ALTITUDE 4000 FT

STANDARD SLING - 11 FT FORWARD
- 8 FT AFT
FLIGHT X8 RUN 14 AAELSS ON
FLIGHT X8 RUN 5 AAELSS OFF

FIGURE 12. EFFECT OF AAELSS II ON LOAD DAMPING AT 40 KNOTS - EMPTY MILVAN

lb payload at 105 kn, which was the aircraft power limit speed. Load to airframe weight ratio was 0.55, the highest experienced in the Edwards evaluation and one of the greatest ever flown during dual load suspension testing with a CH-47C aircraft. A similar AAELSS I PIO test at 80 kn (with about half the AAELSS II payload) is shown at the bottom of the figure for comparison. Note the degraded levels of performance resulting from actuator stall in the earlier system.

As seen in Figure 13, the pilot excited the load by slowly moving the longitudinal stick back and forth at the load natural frequency. Load motion with respect to the fuselage gradually built up as the pilot manipulated the controls in response to perceived acceleration cues. After about four to five cycles, a fully developed case of PIO existed (with measured longitudinal acceleration peaks exceeding $\pm 0.1g$), and the pilot was unable to reduce load swing amplitude by further control application. At this point, AAELSS was engaged. Load motion damped out smoothly in about three cycles with the pilot still in the loop.

While the pilot was working his way "out" of the control loop subsequent to AAELSS activation, measured load damping was on the order of $\zeta = 0.1$. This level of damping is about one third of that provided by AAELSS with the pilot out of the loop, as shown at the top of Figure 11. The significant fact in this example of PIO is that even at reduced levels of damping caused by pilot inputs, the system was still capable of rapidly stopping the unwanted oscillation. Decoupling the load pendulum from the airframe, by introducing aircraft attitude information into the control laws, would improve the situation substantially by removing the aircraft as a source of load disturbance.

Other limited evaluations with lower payload modules (11,800 and 4,700 lb) showed no PIO tendencies with AAELSS on, and little indication of its potential development with the system off. The pilot did feel, however, that the heavier payloads (especially those in excess of 10,000 lb) were susceptible to PIO when the proper gust or control excitations were applied.

1.8 SUMMARY AND CONCLUSIONS

1. The Edwards AFB AAELSS II evaluation established the feasibility of using a system of this type to stabilize external loads on tandem rotor and HLH-type aircraft. With modification, the system concept is also applicable for single-rotor helicopters as well.

   All pretest objectives were met during the Edwards program.

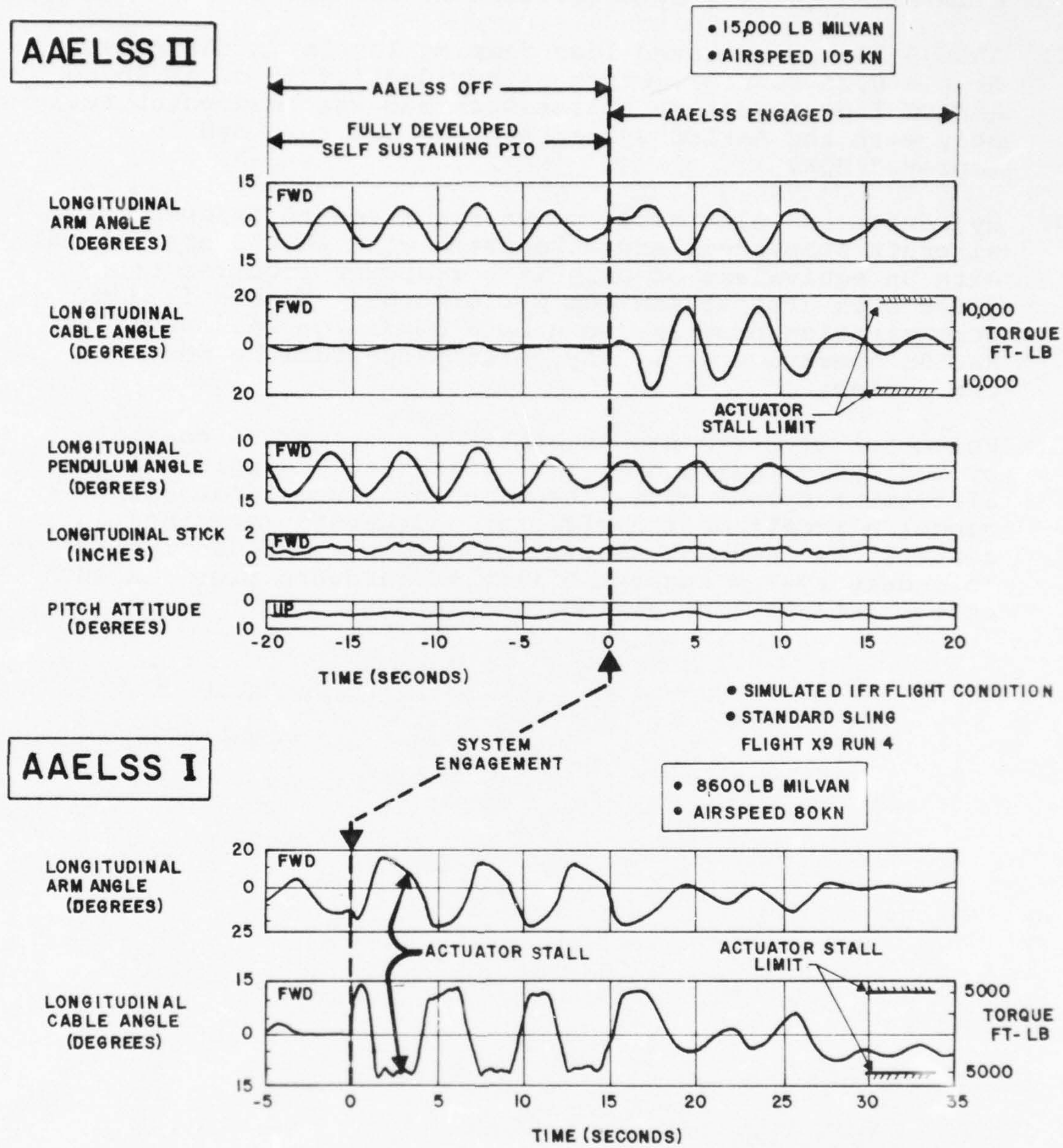


FIGURE 13. RECOVERY FROM LONGITUDINAL PILOT-INDUCED OSCILLATION BY ENGAGING AAELSS SYSTEM

2. AAELSS effectively eliminates any tendency for an external load to cause longitudinal PIO under IMC conditions. Should PIO develop with the system disengaged, it can be eliminated quickly by activation of the system.

3. AAELSS II demonstrated load damping levels in the range of $\zeta = 0.25$ to 0.39, which either duplicated or exceeded AAELSS I performance. Pilot workload was reduced appreciably with the AAELSS system engaged and resulted in improved HQR.

4. Hydraulic and electrical power requirements imposed on aircraft subsystems and associated with AAELSS are minimal with an equivalent of only 16 horsepower required to drive both arms at maximum performance. In the flight demonstration program, no unsafe condition was caused by AAELSS operation or by any anticipated failure modes of the system.

5. Potential improvements in AAELSS operation are possible by modifying the control law package to decouple load/airframe response modes (by using attitude feedbacks to cancel aircraft motion effects). Other improvements in control law feedback shaping have been shown (analytically) to reduce system susceptibility to hardware problems such as the lateral long-period oscillation.

2.0 AAELSS II DESIGN

AAELSS II detail design development has been oriented primarily toward requirements for a 10-to 15-hour flight demonstration of the system on a CH-47C helicopter. Major design features include:

- Double the load-carrying capacity of the original AAELSS (to 20,000 lb), while providing capability for PIO elimination in IMC flight and pendular damping levels exceeding 25% of critical, without overloading aircraft subsystems or creating unsafe conditions.

- Redesigned arm and cable riser components to demonstrate applicability of the active arm stabilization concept on an HLH-type aircraft with winchable cargo hoist cables.

- Improved cable and arm sensor packages to eliminate hysteresis associated AAELSS I problems, and increased capacity hydraulic actuators (twice AAELSS I sizing) to prevent actuator stall over a reasonable range of load motion.

The foundations of AAELSS II design, including control law selection from several candidates, application of actuator sizing techniques, implementation of system improvements to overcome AAELSS I deficiencies and other details were established in the preliminary design study cited in Reference 2. With the exception of the methodology for attaching the arms to the fuselage, and use of Teflon-lined (rather than needle) bearings, the final AAELSS II remained essentially the same as defined at the completion of the Reference 2 work. Because of this similarity, only the highlights of AAELSS II design analysis and implementation are reviewed in this section of the report.

Requirements for AAELSS are noted first, followed by a brief discussion of how the active-arm concept is mechanized. AAELSS II design features are summarized, and then specifics of the design implementation are covered in each of the principal areas of interest, including:

- Handling qualities and electrical system design

- Dual suspension cg and flight envelope constraints leading to application of SRD-84 hook release system technology for AAELSS

- AAELSS structural design

- AAELSS unit design

- AAELSS hydraulic system design

2.1 REQUIREMENTS FOR AAELSS

Automatic stabilization of externally slung loads is required whenever any of the following improvements in helicopter productivity is needed to accomplish the mission:

- Full envelope IMC flight with external payloads
- Precision load placement in hover
- Transportation of unstable loads

The AAELSS IMC mission requirement as described in Section 1.2 is related to the elimination of PIO with high payload to airframe weight ratios, and to a reduction in pilot workload through improved handling qualities resulting from increased pendular damping. In the hover precision load placement task, the AAELSS is needed to reduce the time required for the load motion to settle out following a disturbance.

Basic sling load damping in hover is very low, averaging 5 to 10% of critical for most practical suspension lengths ; and the period of oscillation is rather long, typically 5 seconds or more. Using the 5% damping figure, unaugmented sling load motion requires about 10 seconds to decay to half amplitude after excitation. Compared to this, AAELSS on damping at 25% of critical, forces load motion to subside five times faster (halving amplitude every 2 seconds).

Examples of precision hover placement tasks where AAELSS damping would be of great value include:

- Location of artillery pieces into final firing emplacement positions, requiring no movement after touchdown
- Loading Milvan containers on transporters or removing these payloads from confined areas
- Erection of construction or bridge-type elements with the helicopter

Application of AAELSS capabilities to the problem of transporting unstable loads is best illustrated in cases where optimum sling suspensions cannot be used on cargo that would otherwise be satisfactory for movement. An example of this would be a Milvan supported on long risers in order to permit extraction of the load from a confined area adjacent to trees or between buildings, etc., where the helicopter is unable to descend low enough for hookup with a standard suspension. Even with standard short slings, problems are possible if the Milvan is flown at an unfavorable angle of attack. This is likely to occur if fore and aft slings are reversed during hookup, producing level or noseup load attitudes that are directionally unstable.

2.2 AAELSS II CONCEPT

The system provides damping by sensing load pendulum angle, and then through a series of automatic control law commands to the arms, forces load motion to subside by moving the suspension attachment point at the end of the arm over the load as it swings. Pendulum angle (between the load line of force and the fuselage) is computed from a summation of cable and arm angle information measured with sensors described later in this section. An overall summary of AAELSS II functional operation with an explanation of how the control laws work is presented in Sections 1.3 and 1.4.2.

The AAELSS damps three oscillatory pendulum modes at the same time, and these are related to longitudinal, lateral, and directional load sway. This damping is accomplished by simultaneous longitudinal or lateral action of both arms in the same direction to stabilize the first two modes. Differential lateral arm motion controls the third (yaw) mode. The front and rear arms both have separate longitudinal and lateral actuators, and each of these powers has a single axis with its own sensors, control law electronics, and so forth.

In the longitudinal axis both arms operate in parallel, and are therefore inherently "single-fail operational" with the same damping capability available after failure, but over a smaller range of load motion. Lateral arm movement, on the other hand, is independently divided between the front and rear units; hence a failure results in assymetric operation. Flight tests discussed in Section 5.0 showed no stability problems arising from this type of assymetric lateral operation within the test envelope evaluated.

In addition to having four separate and independent axes that effectively prevent coupled failure modes, the AAELSS also has another advantage in that it is not a part of the aircraft stability augmentation system (SAS). This "stand alone" capability means that the AAELSS will continue to operate regardless of the status of the SAS. A proposed AAELSS improvement discussed in Section 5, to decouple airframe and load motion through use of aircraft attitude information in the AAELSS control laws, could be incorporated without interfering with SAS signals, by providing AAELSS with its own attitude gyro package. As shown in Figure 3, the AAELSS is interconnected to aircraft subsystems only in the area of hydraulic and electrical power supplies, and these are manually protected from one another by the appropriate electrical and manual shutoff valves, switches, and circuit breakers, etc., described later.

2.3 DESIGN FEATURES

2.3.1 System Description

The general arrangement of major AAELSS components and subsystems is sketched in Figures 2 and 3, and photographs of the forward unit installed on the test aircraft are presented in Figures 14 and 15. As shown in these drawings and photos, significant elements of the system are:

1. The hollow rigid arms, which are universally suspended from the aircraft through pivot and pillow block assemblies, mounted with Teflon-lined bearings on load distribution structural attachment frames Huck bolted to the fuselage bottom

2. The system components applicable to the winchable cargo hoist approach include:

   - The central cable tension member composed of a 9-ft section of HLH cargo hoist cable, pinned at the top of the arm for the demonstration system, but easily adaptable for later winch application

   - The bell-shaped guidance ferrule installed at the bottom of each arm to prevent excessive cable bending or kinking

   - The cable cage follower and synchro that form the sensor system for measuring cable angles relative to arm motion, and arm position relative to the fuselage

3. The hydraulic actuators and associated electrohydraulic control components mounted on panels installed on each unit, and the interfacing subsystem connecting both AAELSS units to the aircraft utility hydraulic supply

4. The cargo hooks and associated release systems, including three electrical and one mechanical method of load jettison

5. The dual inverted "Vee" nylon sling suspension system connecting the hooks to the payload

Overall geometry and layout of the AAELSS arms and rigging draws heavily upon prior experience with tandem hook suspension systems evaluated in the SRD-84 program (References 4 and 5), and on the Model 347 Demonstrator aircraft both before and during the HLH effort. As indicated earlier, the principal

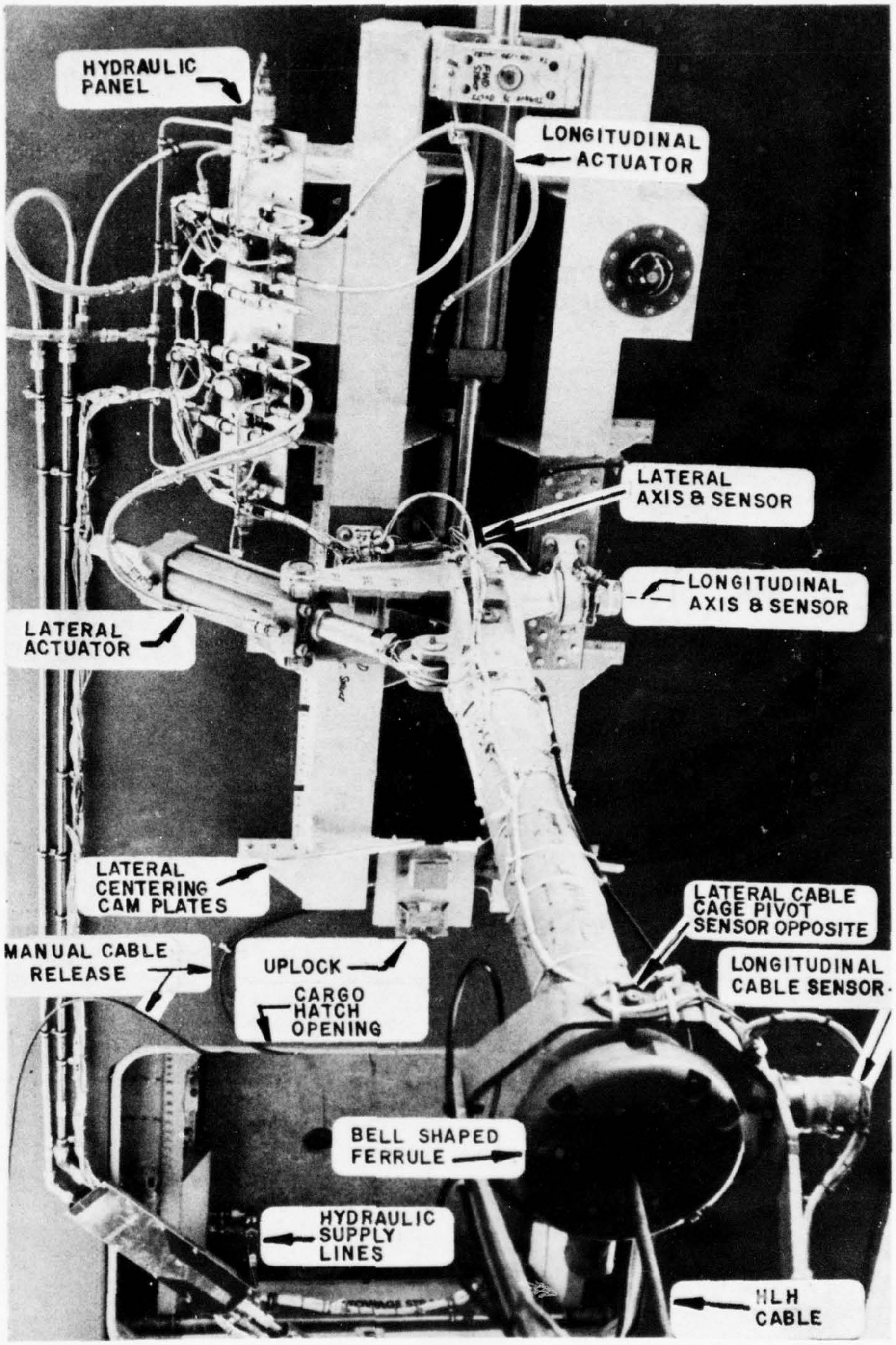


FIGURE 14. FRONT AAELSS ARM, INSTALLATION ON FUSELAGE BOTTOM LOOKING UP AND AFT

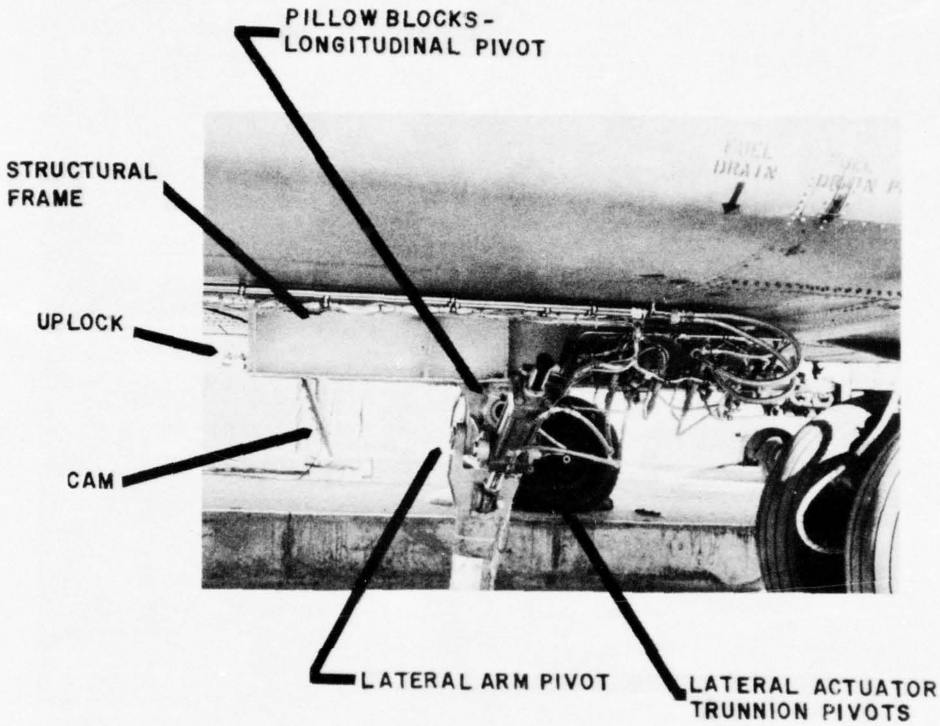


FIGURE 15. SIDE VIEW OF UPPER ARM, HYDRAULIC MODULES AND STRUCTURAL ATTACHMENT FRAME (AIRCRAFT OVER PIT)

benefit of separating the hooks longitudinally in the tandem configuration is to provide yaw constraint of the load with various rigging combinations and payload shapes.

In the AAELSS II installation, the arms are mounted 12 ft apart and equi distant from fuselage station 340 (which is 9 inches aft of the centerline of rotors). The 12-ft separation is 20 inches shorter than that in the SRD-84 system in order to take advantage of distributing the load from each arm uniformly between several fuselage frames (instead of one), through an external structural attachment framework of the type sketched for the aft arm in Figure 16.

In determining arm (or hook) longitudinal separation, the units are placed as far apart as practical to restrain load yaw motion; and at the same time this distance is limited by cg travel and available longitudinal control considerations subsequent to a failure of one suspension, and retention of the load by the other arm (which is a major AAELSS structural design consideration discussed later).

The aft arm assembly shown in Figure 16 is identical to the forward unit, except that it is turned 180° on the aircraft bottom to permit both arms to retract toward the cargo hatch, for ease of hook stowage in the cabin during landings and takeoffs. Components of both arm assemblies are interchangeable, and the function and design of each is covered later.

2.3.2 Revision from Preliminary Design

EXTERNAL FRAMEWORK - Because of the necessity for rapid installation and removal of the demonstration AAELSS II from the test aircraft, a substantial modification was made in the original design approach for attaching the arm assemblies to the airframe structure. As envisioned in the preliminary design described in Reference 2, a significant amount of internal "beef up" within the fuselage was required to transfer arm loads into the airframe. Installation and removal of this internal structure would have been both costly and time consuming from the standpoint of benefits gained.

A revised attachment concept was developed to transfer arm loads through a rigid external box beam distribution structure directly into the fuselage frames and skin as shown in Figure 16. In this approach, the external framework was attached to the fuselage frames by first removing the rivets holding the skin on, and then replacing these with 3/16 inch Huck bolts inserted through the framework. In this manner, vertical and lateral loads were uniformly distributed over four fuselage frames for each arm. Longitudinal shear loads were fed directly into the aircraft skin through riveted plates attached to the top of the external beam distribution structure.

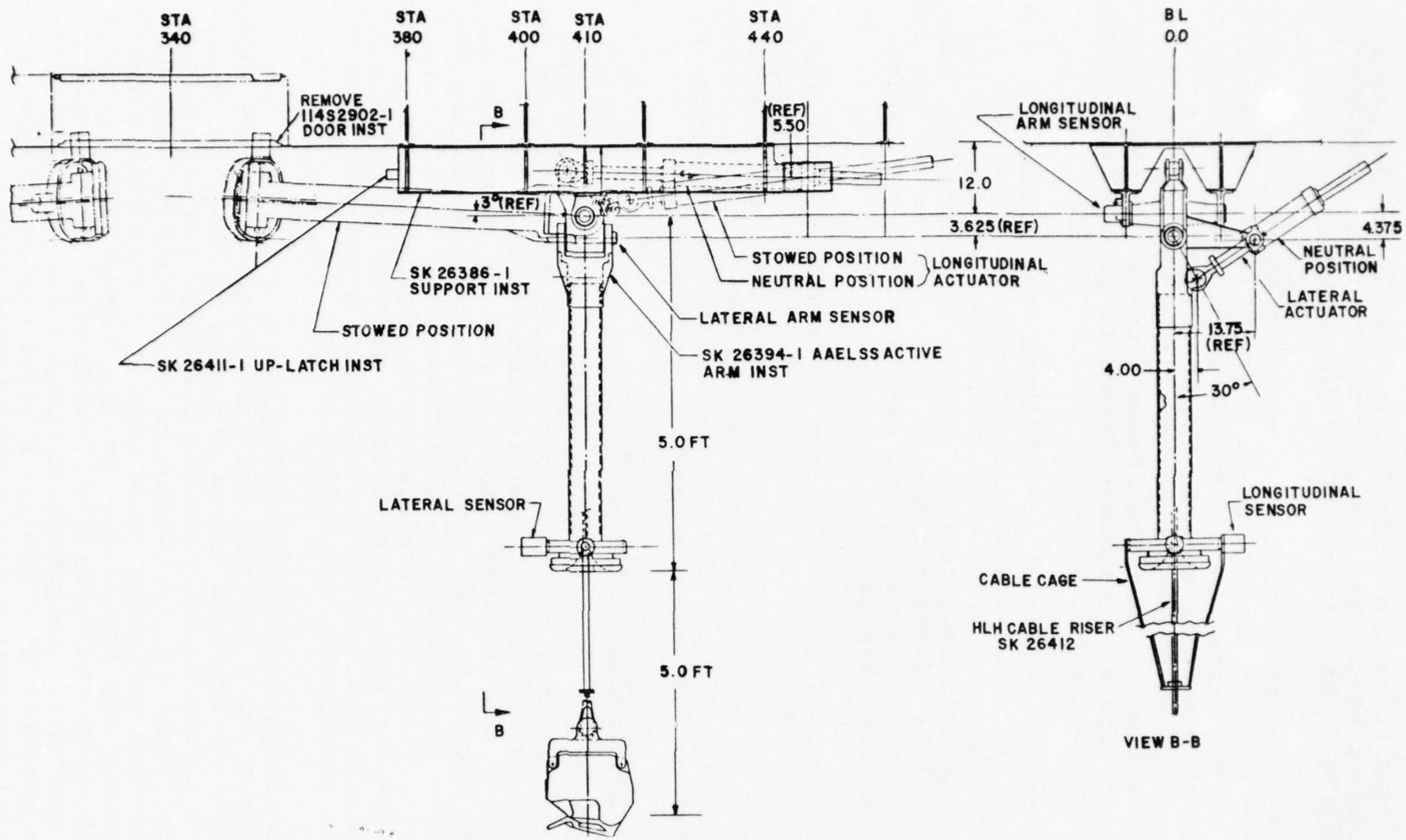


FIGURE 16. LAYOUT REAR ARM INSTALLED ON CH-47C - AAELSS II

The external distribution frame system worked extremely well throughout the test program. The validity of using this approach for the test installation was confirmed when less than one week was expended in system installation, and only three days were required for removal and refurbishment of the test vehicle.

ARM AND ACTUATOR BEARINGS - A second departure from the preliminary AAELSS design involved a change in the type of bearings used for arm and actuator support. Applying technology developed in design of the HLH upper controls, a decision was made to use Teflon-impregnanted dacron lined plain bearings, instead of needle bearings in the AAELSS mechanization.

Teflon-lined bearings were found to be superior in nearly all respects, requiring fewer parts, no lubrication, and no special design to carry side thrust loads (except for a simple coated flange on the end of the cylindrical bearing sleeve). These bearings were also substantially lighter and more compact in the final design application, and showed superior resistance to fretting throughout both ground and flight test programs (described in Sections 3.0 and 5.0).

2.3.3 Arm and Cable Riser Component Sizing

To minimize hydraulic power requirements for a most efficient operation, AAELSS arms should be as long as possible. Lengthening the arm would not necessarily require an increase in cross sectional size or section modulus, since the moment produced by the arm (for a given load displacement) is fixed by the stall torque available. Limitations to arm length would normally be established by considerations of drag, arm stiffness, weight, or retraction scheme used to stow the units for landing.

In the case of AAELSS II, the 5-ft arm length is dictated almost completely by the necessity to fold both arms toward one another for hook retrieval through the hatch. With a 12-ft separation established by sling/hook failure considerations mentioned earlier, the arm ferrules extend just into the hatch area as shown in Figure 16 when retracted.

As in the case of the arm, the cable riser length also must be achieved through compromise. From the standpoint of static load stability, the shortest length possible is the best. In order to measure cable relative to arm angle, however, some length of cable is required beneath the ferrule in order to permit installation of the cable synchro cage follower assembly. This cage assembly must be as long as practical to prevent kinematic errors in measuring cable angle which results when the cable bends around the ferrule.

In the final AAELSS II installation, the total riser length of 9 ft provides just enough cable beneath the ferrule to keep angular measurement errors in the range of 3 to 5% at the static stall torque arm displacement. As is readily apparent in Figure 1, very little cable extends beneath the cage and above the hook assembly.

2.3.4 Other Design Features

RETRACTION AND UPLATCH CAPABILITY - To eliminate a major AAELSS I fault, the new system was designed with automatic retraction capability, and a manually activated uplock that maintains the arm in its fully retracted position with power off. In the earlier device, a ground crew was required to lock and unlock the arm from its stowed (retracted) position every time the system was used.

The simple "door latch" type uplock is shown in Figures 14 and 15. It was manually operated throughout the test program from the flight engineer-observer station discussed in Section 5.3.1. To deploy the arms, the "up" hydraulic switches were activated by the flight engineer and the latch was released with a lanyard. When these switches were turned off, the arms deployed downward.

As mentioned in Section 5, arm retraction can be initiated either by the pilot (through his AAELSS control panel) or by the flight engineer through his hand-held switch box. Full retraction and uplock latching is accomplished automatically, as the arms are guided into the uplatch by a "Vee" shaped cam arrangement mounted on the structural attachment frame.

PARALLELING SLING - Another design feature of AAELSS II is the use of a paralleling sling between the hooks to prevent rotation of the HLH cable tension members. These cables are "lag lay" wound in one direction only during manufacture, and are intended to be used in pairs (wound in opposite directions) in the HLH winch installation. The paralleling sling stops the cables from unwinding, thereby preventing an overtorque stress concentration for which the cables are not designed.

A secondary benefit derived from use of the paralleling sling is that it "pulls in" the aft "vee" sling attachment apex, thereby conserving longitudinal actuator travel from its required trim position in forward flight.

2.3.5 Design Variation for Nonwinchable Load Suspensions

The design of AAELSS II was considerably influenced by requirements to demonstrate applicability of the concept with a winchable cargo hoist system. If this requirement were not retained in any further refinement of the system, AAELSS design would undoubtedly have a substantially altered character with the cable tension member and ferrule components eliminated, and the hook probably gimballed directly on the bottom of the arm as described in Reference 2. This configuration is similar to AAELSS I, but would incorporate improved Teflon-lined bearings at the hook to eliminate hysteresis, and longer arms with rearward retraction for greater operational efficiency and safety.

2.4 HANDLING QUALITIES AND ELECTRICAL SYSTEM DESIGN IMPLEMENTATION

The AAELSS II has been designed to meet specific criteria summarized previously in Section 1.4.1. These criteria apply to design implementation in the areas of handling qualities and electrical system, structures, hydraulics, and hook release systems. Details of the design philosophy followed, and the system components developed in each of these areas is covered in the remainder of this report section, starting with a synopsis of capacity sizing to produce desired levels of damping.

2.4.1 Capacity Sizing to Provide Damping

In order to size hydraulic actuators and servo valve flow rates, a trade study produced AAELSS II stall torque requirements of approximately twice those of the AAELSS I capacity (10,000 ft-lb), and valve flow rates averaging 2 gpm, while providing load damping in excess of 25% of critical over a desired load displacement range of ±2 ft. These parameters were selected on the basis of the following considerations.

To begin with, a pendular damping level target of 25% was adopted as a minimum acceptable criterion, with a desired range of about ±2 ft over which this damping was to be effective. These criteria are based upon satisfactory AAELSS I test experience while performing operational maneuvers and PIO investigations with external loads. From the discussion of capacity sizing presented earlier in Section 1.4.2 and using Figure 7, it is recalled that stall torque (where actuator force is a maximum) must be increased in order to broaden the area over which a given damping level can be maintained. Alternatively, if a load displacement range is selected first, damping can only be increased by upping stall torque capacity. Increasing stall torque requires a larger actuator and expenditure of more power.

In order to efficiently utilize the aircraft's utility system capacity and to minimize power requirements for the AAELSS, two simple relationships were applied in the sizing task:

$$HP = q \cdot \Delta P \text{ and } \frac{Q \cdot V_t}{\ell} = HP$$

where HP = power
q = flow rate
ΔP = pressure
Q = torque required
V_t = linear arm velocity at the ferrule
ℓ = arm length

With damping, load displacement, and arm length preselected, it was relatively easy to iteratively arrive at minimum torque requirements commensurate with flow rates available from the utility system. With maximum velocity of the arm determined by servo valve flow rate, this rate was adjusted so that it was just adequate to meet required performance at the stall torque level. Final parameter selections were adjusted to agree with the capabilities of readily available hardware as listed below:

• Actuator Stall Torque	11,800 ft-lb
• Maximum Arm Velocity	14°/sec or 1.2 fps at the arm end
• Average Servo Valve Flow Rate	2 gpm with accumulator assist for peak operation
• Maximum System Flow Rate	8 gpm or approximately 16 horsepower

As described in the final part of this section, commercial hydraulic cylinders were combined with CH-47 SAS servo valves and other aircraft components to satisfy arm drive system requirements to meet the 25% damping and ± 2 ft load displacement criteria.

2.4.2 Electronics and Switching Functions

The Figure 17 schematic details major components of the AAELSS II electrical and control systems installed on the test aircraft for flight demonstration and optimization. On the right are cockpit panels, switches, etc., available for use by the pilots; and shown in the center of the chart are various elements of the system installed at the flight engineer/observer station (which is also pictured in Figure 18). Illustrated on the left side of Figure 17 are the principal electrical equipment items located outside the fuselage, including synchro-angle sensors, hydraulic control components, and uplock signal transducers for each arm.

Operation and function of most of the AAELSS associated items in the cockpit are covered in Flight Test Section 5.3.1. During

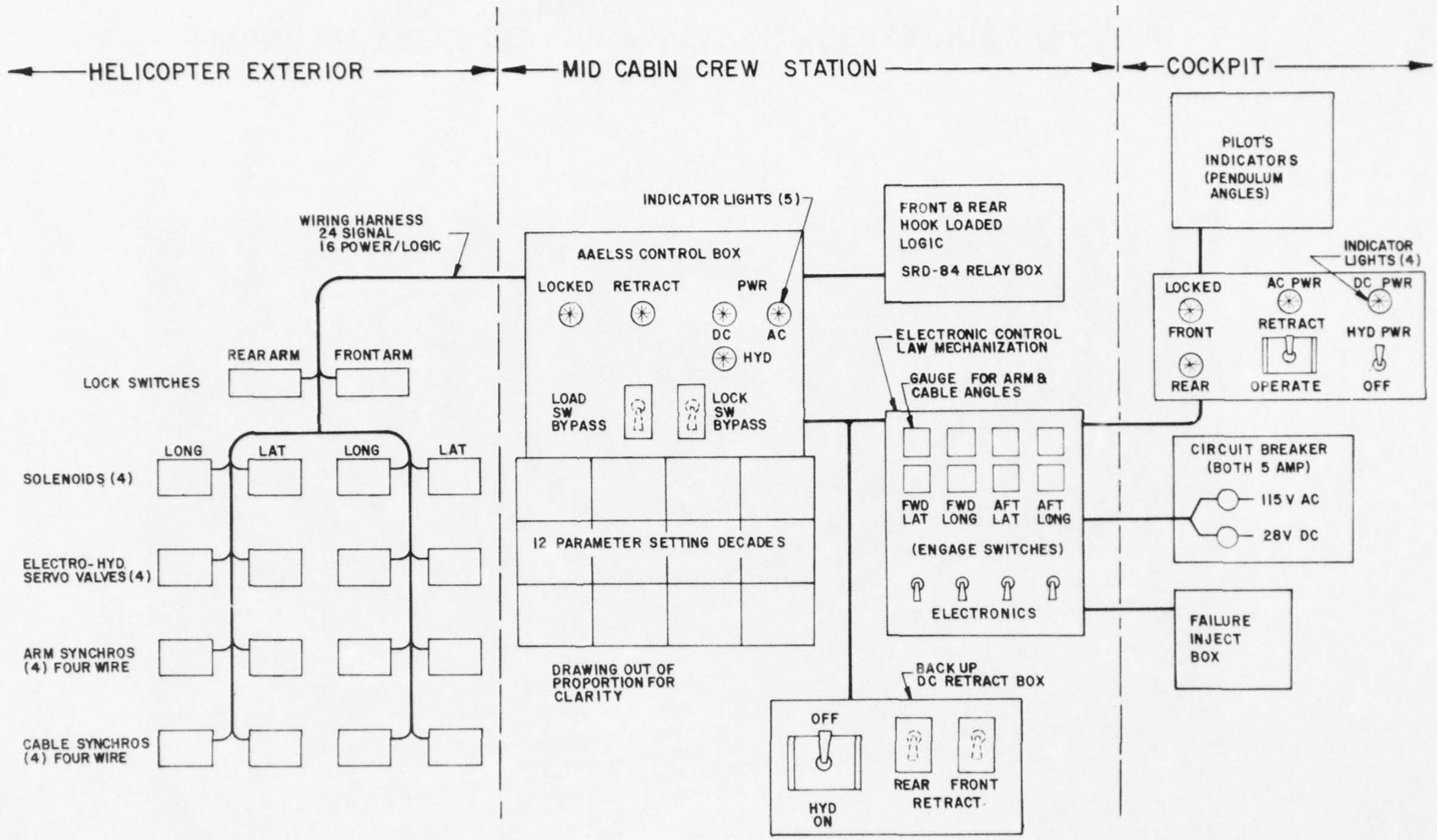


FIGURE 17. AAELSS CONTROLS & WIRING

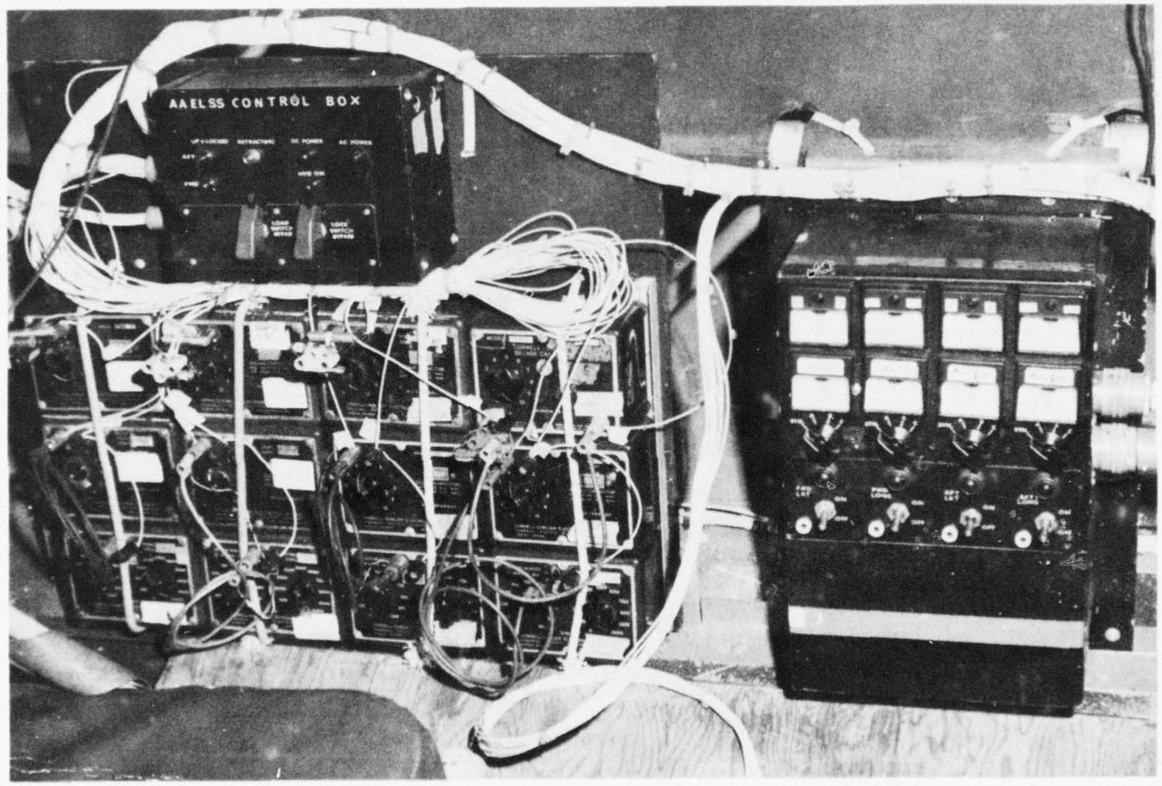


FIGURE 18. AAELSS II CREW STATION ELECTRONICS PACKAGE
AND CONTROLS

the flight program, the copilot was responsible for turning the AAELSS on and off, for monitoring maximum load pendulum angles experienced in the buildup, and for extending and retracting the arms as required. With the arms deployed and "operate" selected, the system was engaged and disengaged through activation of the hydraulic power on/of switch.

By placing the master switch in the "retract" position, the arms are automatically retracted onto the uplock mechanism as described earlier. Once these uplatches are locked, the system is automatically depressurized (with the actuators in bypass), and the arms are then retained in the "up" position through action of the mechanical uplock.

The heart of the AAELSS control system is located at the flight engineer/observer station in the "control law electronics" and "AAELSS control" boxes. Within the electronics box, each actuator has its own control law card and "on/off" switching for engagement. The cards are identical to each other, except for the minor longitudinal axis jumper function (which cancels out steady trail angles due to payload drag) mentioned earlier in discussion of the Figure 6 control law block diagram. The individual electronic cards are relatively uncomplicated, with only seven operational amplifiers and three transistors required to perform all shaping and switching functions, including demodulation of both arm and cable synchro signals for each axis.

Along with the electronics and control panel packages at the observer station is a group of 12 standard decade boxes for adjusting control law gains, time constants, etc. When sufficient range adjustment was not available within the decade scale, external resistors were utilized to accomplish the task. This decade adjustment capability is not required in any production model AAELSS application because the control system parameters would be fixed.

2.4.3 Safety Considerations in AAELSS II Demonstration System Electronics Operation

AAELSS II electrical and hydraulic components provided for the flight test evaluation were, for the most part, nonredundant in function in order to conserve funds for other aspects of this exploratory program. With exception of inherent longitudinal failure redundancy discussed earlier, each axis was capable of experiencing electrical or hydraulic faults which could lead to actuator hardover, or system go-dead situations. For simulating these potential occurrences, a "failure-inject-box" was used in the test program to facilitate airspeed and envelope buildup expansion with the system engaged.

None of the simulated hardover tests indicated any problem whatsoever in recovery maneuvering throughout the evaluation envelope; but it is felt that some redundancy would probably have to be provided in the lateral axis (most likely in the area of sensors or control shaping electronics) for a mature operational production AAELSS. The redundancy requirements have not been explored in depth, and would therefore have to be considered in future development of the system concept.

To protect the ground crew from possibly exciting a powered AAELSS arm during load hookup, the system is automatically disabled hydraulically until both hooks are loaded. The required "load on the hook" interconnect signal is generated by the SRD-84 system any time both hook loads exceed approximately 65 lb. The loading signal for each hook is also used for the "auto jettison" payload release mode, which is described later.

In addition to the hook load safety features, AAELSS II also has a backup arm retraction capability to fold the arms when AC power is not available. This system is operated by the flight engineer-observer, and utilizes DC power control of the servo valves only, bypassing the normal AAELSS electronics and logic used by the pilot's retraction system.

In any production version of the AAELSS, electronic packaging could be simplified and compacted so that all necessary system controls were located in the cockpit for pilot access. Backup retraction and other switching systems provided for the observer could easily be consolidated on cockpit panels, and only the emergency load jettison capability would have to be retained at the crew-chief station amidships.

2.5 ENVELOPE CONSTRAINTS LEADING TO APPLICATION OF SRD-84 HOOK RELEASE TECHNOLOGY FOR AAELSS

In the AAELSS I test program, emergency load jettison was possible by releasing the entire beam mounting structure to which both arms were attached. AAELSS II did not utilize this method of arm installation, and therefore alternative load jettison approaches were investigated for application with the new system. Among these was the SRD-84 tandem hook approach, which had already been qualified for loads up to 19,000 lb at the time AAELSS detail design began. Because of the many attractive advantages in using an existing system that would meet all AAELSS requirements, SRD-84 was selected for AAELSS II.

Application of SRD-84 technology in AAELSS design is discussed in this section of the report, following a description of the effects of dual-point load suspension on the allowable cg envelope permissible with an AAELSS equipped aircraft.

2.5.1 Effect of Dual-Point Load Suspension on Aircraft CG Envelope

Figure 19 shows the effect of dual-point load suspension on the center-of-gravity envelope for a CH-47C helicopter. The cg diagram shown in this figure was developed in conjunction with SRD-84 testing, and was then modified for application with AAELSS II. The dashed envelope represents the normal CH-47C loading envelope, the cross hatched area is the permissible rearward extension possible with dual-point external loads attached, and a cruise guide indicator (CGI) is installed for the AAELSS demonstration.

AAELSS is designed to carry 20,000 lb payloads, and under normal loading conditions with 50% distribution on either arm, produces a loading curve that is only slightly behind the normal CH-47 aft limit (approximately 2 in.) for most of the gross weight range. The 50% loading curve shown in the center of the diagram represents an addition of a 15,000-lb test payload (maximum permissible for the Edwards demonstration because of OGE hover performance requirements) to the aircraft, followed by fuel topoff to the 45,000-lb OGE hover limit.

The 60-40 split line to the right of the 50% curve represents the most critical design condition assumed for AAELSS, and at 46,000 lb maximum gross weight is approximately 14 in. aft of the normal envelope. Operation in this extended area of the diagram is satisfactory when CGI limits are observed because the instrumented link and actuator (CGI components) are in the aft rotor upper control system, which becomes critical for rearward loading situations.

Two additional loading curves are shown on the diagram, representing emergency situations where either the forward or aft sling suspension fails, and the load is then retained by the other arm with the aircraft flying at low speed. Analysis indicates that adequate longitudinal stick is available to control the aircraft after this type of failure. The SRD-84 system automatically jettisons the load above 60 kn after a sling failure, but the hook and AAELSS suspensions are designed to contain the load on the unfailed arm (if necessary after a failure) before the pilot initiates a manual release. Exactly how these manual and "auto jettison" SRD-84 system features operate is described in Section 1.4.1.

2.5.2 Evaluation of Potential Load Suspension Failure Modes

At the beginning of the tandem suspension system development, a substantial analytical and wind tunnel effort (reported in Reference 7) was initiated to determine load (and aircraft) response characteristics, after suffering various types of sling failures. Two critical conditions were identified: one

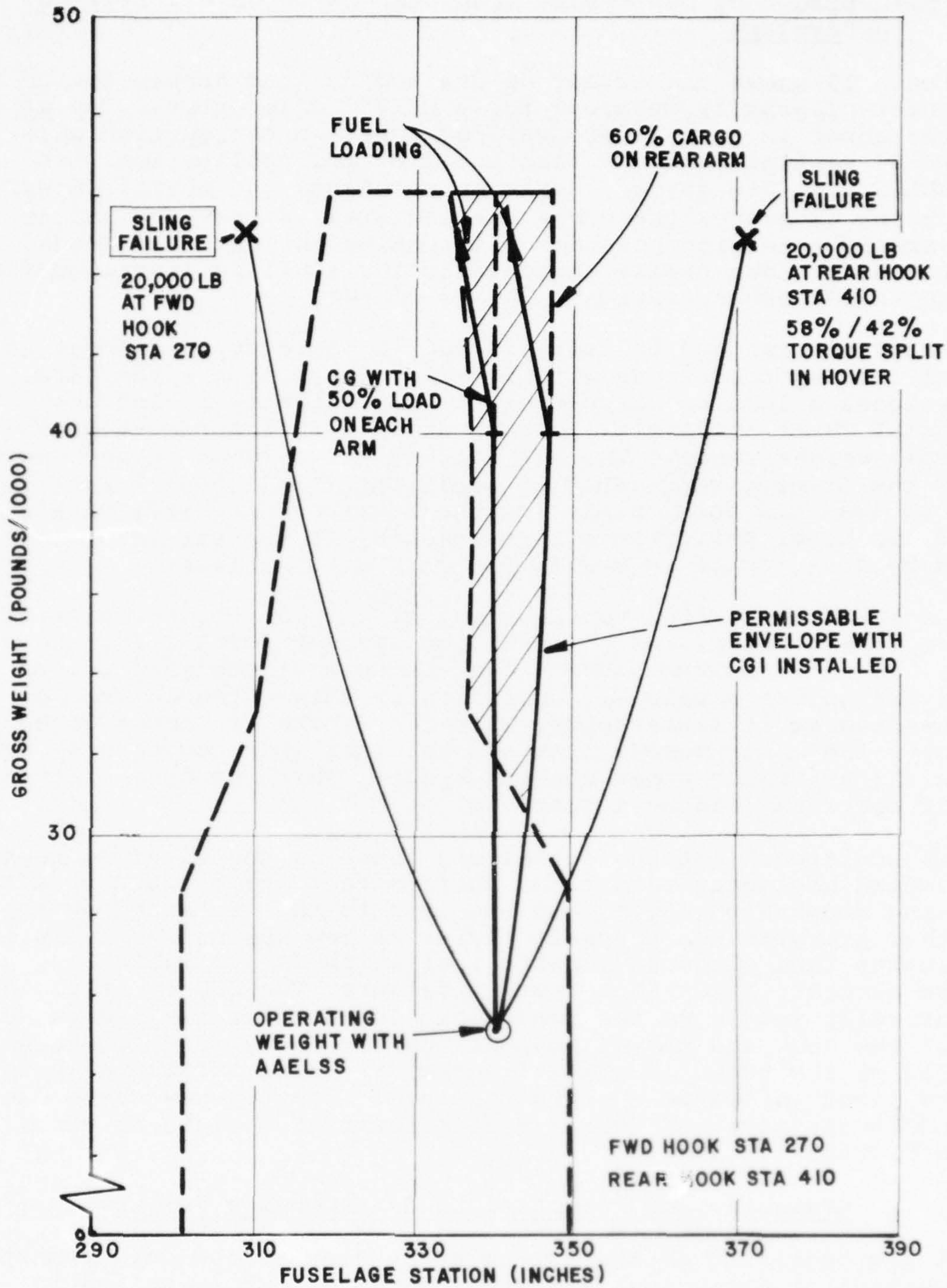


FIGURE 19. CH-47C/AAELSS II DEMONSTRATION CENTER OF GRAVITY ENVELOPE FOR MULTIPLE SUSPENSION

with a light (empty) Milvan container in high-speed flight (Figure 20), and the other with a ballasted 20,000-lb load, under similar conditions (shown in Figure 21).

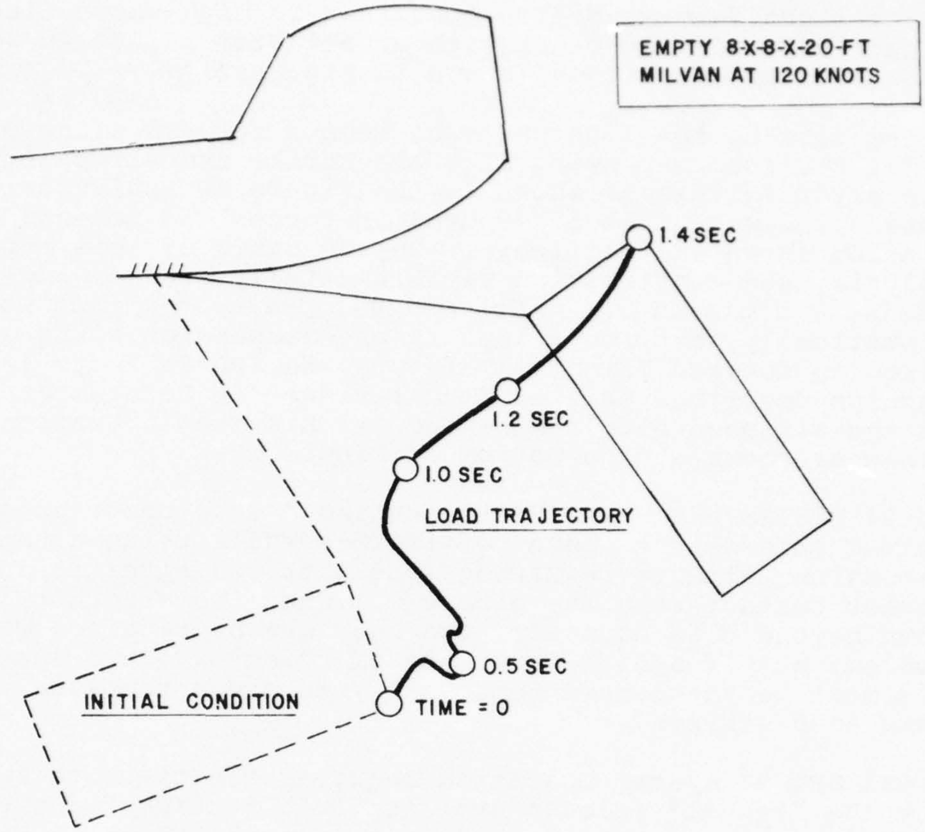
In the case of the light Milvan, when a forward sling or hook fails, the load may swing back and strike the aircraft very soon after failure, as shown in the Figure 20 analytical time history. Powerful load aerodynamic forces and moments cause the gyration shown in the figure. On the basis of this type of analysis, and confirmation with inertially scaled wind tunnel models, a decision was made to develop a system that would automatically jettison a load if one suspension sling or hook failed in forward flight. This was the SRD-84 "auto jettison" function described earlier (and reviewed in References 4 and 5), and the airspeed envelope beyond which system operation is required as shown at the bottom of Figure 22.

SRD-84 SYSTEM USE - The "auto jettison" envelope represents the maximum safe flight speed permissible while using a tandem sling suspension, without requiring load jettison after failure to prevent contact with the aircraft. When the aircraft is not flown beyond this boundary, the load may be retained without problem; but if speeds in excess of this curve are used, the load must be jettisoned immediately to prevent possible airframe load strikes.

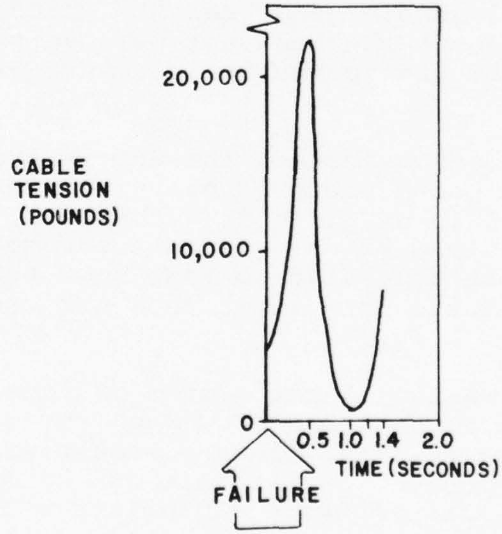
Normal SRD-84 system operation requires the pilot to switch from the "manual" release mode to "auto jettison" above 60 kn while using the overhead hook release panel shown in Figure 23. This would protect the aircraft in the event of sling failure for loads in excess of 3,000 lb gross weight (which, for all practical purposes, is about the lightest payload possible while flying an "aircraft transportable" aluminum 8-x-8-x-20-ft commercial container).

With the auto jettison mode selected, the SRD-84 system automatically releases both hooks whenever either senses a loss of load (i.e., less than 65 lb on the hook mechanism), if, and only if, this "loss" of load signal persists for more than 0.5 sec. The delay is incorporated so that some type of momentary gust excited load motion or jitter does not cause an inadvertent load jettison.

To assist the pilot, a warning light system is incorporated in the SRD-84 installation to tell the crew when the hooks are loaded and when 60 kn is reached, thereby requiring selection of the "auto jettison" mode. The aircraft can be flown faster without switching, but load jettison capability would then depend upon pilot manual operation through his (or the copilot's or crew chief's) load jettison switch on the sticks or cargo hoist pistol grip amidships.

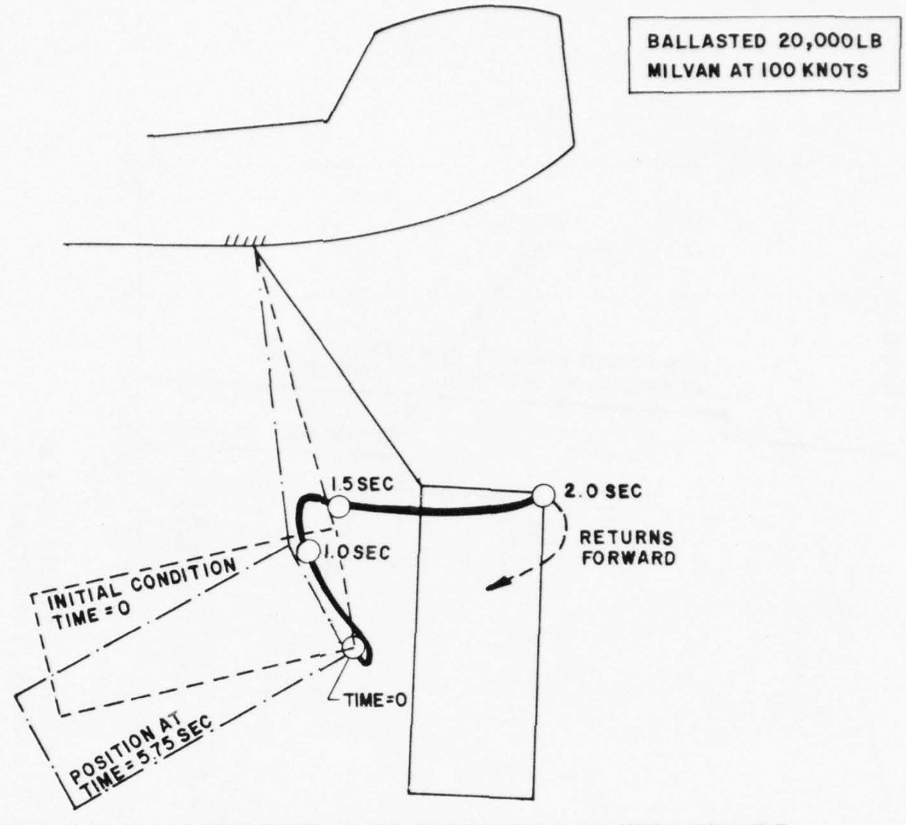


LOAD TRAJECTORY AFTER SLING SUSPENSION OR HOOK FAILURE

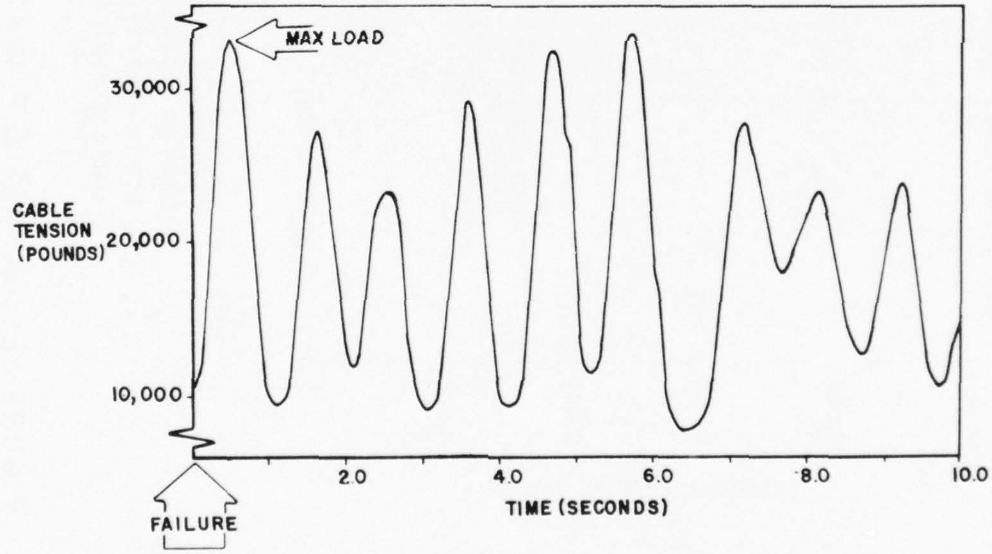


LOAD TENSION IN SURVIVING ARM / CABLE TENSION MEMBER

FIGURE 20. EMPTY MILVAN FORWARD SLING FAILURE

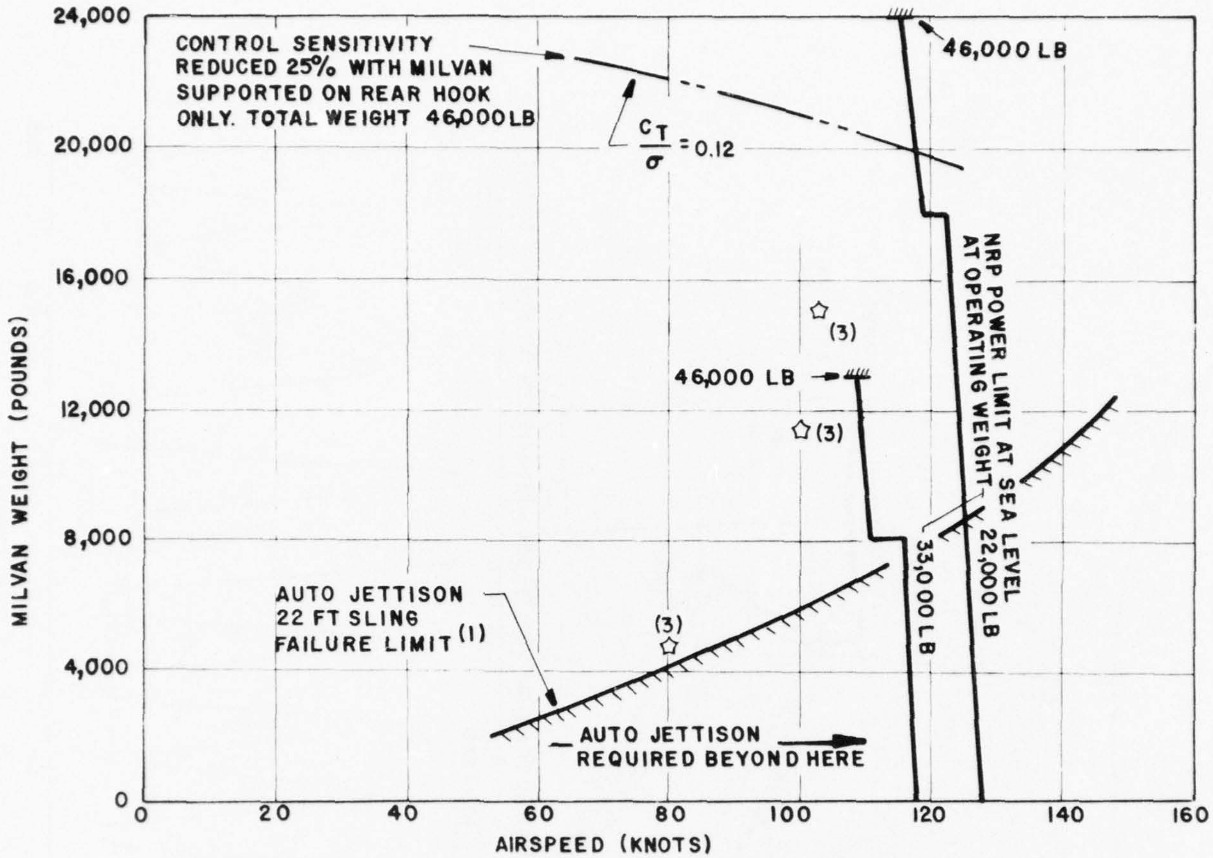


LOAD TRAJECTORY AFTER SLING SUSPENSION OR HOOK FAILURE



LOAD TENSION IN SURVIVING ARM / CABLE TENSION MEMBER

FIGURE 21. 20,000-LB MILVAN FORWARD SLING FAILURE



NOTES:
1. BASED ON FARNBOROUGH (RAE) WIND TUNNEL DATA & THEORETICAL DYNAMIC ANALYSIS PERFORMED FOR SRD-84 PROGRAM
2. BOX fe = 100 FT^2, AAELSS fe CALCULATED = 17 FT^2
☆ 3. MAX AIRSPEED ACHIEVED IN AAELSS II TEST PROGRAM

FIGURE 22. AAELSS II FLIGHT TEST DEMONSTRATION ENVELOPE - CH-47C

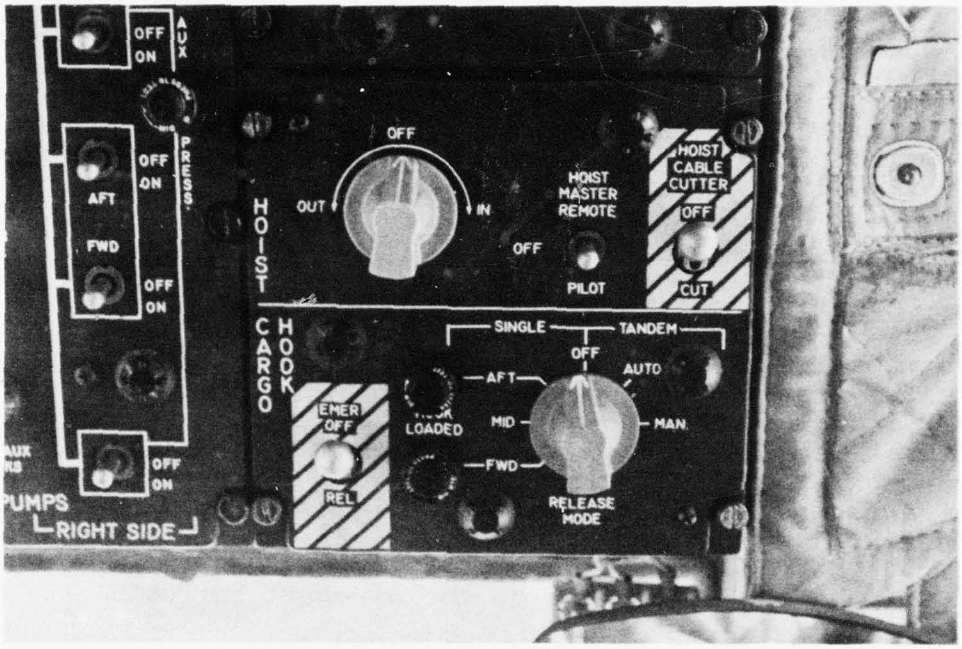


FIGURE 23. PILOT'S CARGO HOOK RELEASE, OVERHEAD PANEL

Additional SRD-84 single hook modes of operation were not used with AAELSS, and are therefore not discussed herein. A complete description of these extra features is included in References 4 and 5.

The time history data presented in Figure 21 for the 20,000-lb sling failure represents one of the conditions imposed in the structural design analysis conducted during AAELSS development. The complete synthesis of the design loading conditions, and the structural analysis of the final system components are included next. An interesting aspect of this analysis is that the controlling conditions for the design of AAELSS and its support structure are related to the failure of a single sling and to the support of the 20,000-lb design load by the remaining unfailed arm. Normal operation of the system at the 2g overload gross weight criteria for the aircraft is less stringent, and therefore was not a controlling factor in AAELSS design.

2.6 STRUCTURAL DESIGN

2.6.1 Description of Structural Materials

Most components of the AAELSS II arm and mounting system were fabricated from 4130 chrome-moly steel. These included virtually all structural parts, except for the 1020 mild carbon steel structural attachment load distribution frames, and Teflon/Dacron bronze bearings. The attachment frame structures were built up from commercial steel wide flange "H" beams, welded together with appropriate intercostal stiffening to provide support. The final "box" was carefully planed to provide a level surface for attachment to the aircraft bottom.

Other elements were built up from machined or welded components, including critical pillow and pivot block arm suspension and drive assembly components that were heliarc welded in some highly stressed areas during assembly. This welding was not entirely satisfactory and caused a problem during the bench test (described in Section 3.0), requiring redesign of the pivot block lateral trunnion and addition of doubler plates to reduce stresses. The redesigned structure solved the problem, and no further difficulties were experienced during either the operational test (Section 4.0) or the flight program described in Section 5.0.

2.6.2 Criteria for Design Loads

Maximum load sway angles utilized in AAELSS II design were influenced by flight test experience with the AAELSS I, and by data generated in the SRD-84 tandem hook program. Design conditions selected for AAELSS II are listed below:

Lateral sway (either direction) - 30°

Forward longitudinal sway - 45°

Rearward longitudinal sway - 50°*

*Aft sway allowance is higher to account for rearward trim due to payload drag

As indicated previously, AAELSS II limit loads are predicated upon an assumed failure of one sling suspension or hook, followed by retention of the payload with the other arm. Design loads (for the unfailed arm) are obtained by considering the 20,000-lb Milvan cargo swinging to the angular sway limits noted above following failure, with intermediate conditions evaluated to determine maximum combined loads. Cable loads relative to arm angle criteria during the failure transient are predicated upon considerations of actuator stall torque capacity, with the actuator maximum load assumed to be 17,300 lb at 3,350 psi system pressure. This assumption is conservative, since aircraft utility pressure is regulated at 3,000 psi.

Table 1 summarizes eight design failure conditions, and the structural loads associated with the resulting failure transients are annotated on the right. The first three cases consider a lateral conical swing subsequent to suspension failure, and the last five are associated with longitudinal motion. Conditions annotated in case 5 are similar to those illustrated earlier in the Figure 21 failure time history.

2.6.3 Analysis of Structure

Using the limit loads developed in Table 1, critical AAELSS II structural components were analyzed, and ultimate margins of safety were calculated as shown in Table 2. Note that all system elements showed positive margins. The upper cap (SK 26386) skin plate safety margin was improved substantially during system installation by bonding the plates to the beam flanges with 2216 Scotchweld Structural Adhesive (in conjunction with using rivets upon which the tabulated margin of safety was based).

In addition to being designed for steady and transient failure limit load conditions, parts subjected to alternating loads were analyzed for fatigue life as well. All fatigue lives listed in Table 2 exceeded 75 hours, except as noted for the pivot block and actuator rod end elements whose calculated lives averaged about five times the expected length of the flight program. Design objectives adopted for the demonstration AAELSS II system installed on the CH-47C called for a 50-hour life (or approximately 7,200 cycles per component) using mean-minus-3σ allowables.

TABLE 1

AAELSS II STRUCTURAL DESIGN LOAD

NOTES: (1) All loads are limit loads

(2) Weight of Milvan 20,000 Lb

CASE NO.	ARM ANGLE (DEG)	PENDULUM ANGLE (DEG)	CABLE TENSION (LB)	ACTUATOR FORCE		PIVOT LOADS ONTO SUPPORT FRAME			
				LATERAL (LB)	LONGITUDINAL (LB)	P_X (LB)	P_Y (LB)	P_Z (LB)	M_X (IN-LB)
LATERAL									
1	30	34.89	24,000	17,300	---	---	13,728	-19,686	173,760
2	15	20.13	24,800	17,300	---	---	8,534	-22,284	164,176
3	-15	-20.14	24,800	-17,300	---	---	- 8,539	-23,282	-164,424
LONGITUDINAL									
4	25	28	28,800	----	17,300	29,900	---	-25,160	---
5	0	3.31	34,400	----	17,300	19,280	---	-35,000	---
6	-22.5	-23	28,000	----	-17,300	-29,920	---	-24,195	---
7	25	22	28,800	----	-17,300	- 5,560	---	-27,008	---
8	0	0	40,000	----	---	---	---	-40,000	---

TABLE 2

SUMMARY OF MINIMUM MARGINS OF SAFETY AND CALCULATED FATIGUE LIVES

NOTE: Components not listed below have ultimate margins of safety greater than 1.0 or calculated lives in excess of 75 hours

DRAWING NO.	ITEM	CRITICAL ELEMENT	TYPE OF LOAD	ULT MS	CALCULATED LIFE (HOURS)
SK 26386	Support Installation	Lower Cap Overboard Center	Bending I/P	0.12	
		Upper Cap Overboard Center	Bending I/P	0.23	
		Attachments to Floor Frames	Tension	0.25	
		Skin Attachment Rivets	Shear	0.23	
		Attachment Plate to Upper Cap	Shear	0	
SK 26394-10	Pivot Block	Lateral Actuator Support Arm	Bending		57
		Support	Weld Shear	0.71	
-12	Pillow Block	Attach to Beam	Beam Flange in Bending	0.10	
		Lug Section	Latl Bending	0.66	
-20	Lift Cable Pin	Section	Bending	0.50	
-22	Thrust Cap	Critical Bending Section	Bending	0.76	
		Bolt	Tension	0.21	
SK 26395-12	Bellmouth	3.7" from lower end	Bending	0.13	
-13	Fitting	Bolts	Shear	0.07	
-18	Adapter	Clevis end root	Bending	0.39	
SK 26361	Actuator	Rod End	Tension		55
114S2402-31	Floor Frame	Lower Cap	Tension	0.13	

Structural qualification testing of the AAELSS II was accomplished in the "bench" test program phase, which was conducted on the HLH cargo hoist tower and is described in Section 3.0.

Structural Weight Breakdown

Table 3 summarizes the component weights of all AAELSS II elements as measured prior to installation on the test aircraft. The final total of approximately 1,750 lb for the demonstration system (not including the weight of hooks, adapters, associated wiring, and slings which would be included in aircraft empty weight for any dual-suspension-configured helicopter) was confirmed by weighing the entire test aircraft with AAELSS II installed and ready to fly.

Because of the exploratory nature of the AAELSS II program, with objectives to get the most information and testing at the least cost, weight minimization was not foremost among the design considerations. The steel framework attachment structure and commercial hydraulic actuator cylinders were considerably heavier than would be required in a production AAELSS installation. An idea of the weight penalty associated with a production version of AAELSS is shown on the right side of Table 3, with aluminum materials substituted for steel where appropriate, and aircraft servoactuators used to replace the heavy commercial components.

Halving the weight of the Edwards test installation appears to be a reasonable possibility for a production four-axis system like AAELSS II. If one of the simplified AAELSS approaches mentioned in Section 5.0 was selected for design (employing either a single forward arm or dual arms with the longitudinal axis only powered), weight could be reduced even further to the 500- to 700-lb range for production. These weights appear to be a reasonable payload trade-off in order to gain full IMC operation with external loads, and potential for precision load placement in hover or flight with unstable cargo.

2.7 AAELSS HYDRAULIC SYSTEM

Discussion of the selection and mechanization of AAELSS II hydraulic system components to meet the capacity, sizing, and sling-load damping requirements introduced earlier in Section 2.4.1 is included in this report section. Unit interfacing with the aircraft utility system is covered, along with failure protection precautions and component specifications.

2.7.1 Interface with Aircraft Utility System

AAELSS II draws power from the existing 3,000 psi utility hydraulic supply on the CH-47C, and thus in normal operation

TABLE 3

AAELSS II WEIGHT SUMMARY

PART	NO. PER SYSTEM	ACTUAL WEIGHT (LB)	PRODUCTION WEIGHT PREDICTION (LB)
Arm Components	2		
Actuators - Lateral		58.7	28.0
- Longitudinal		87.7	56.0
- Gimbal		25.5	10.0
Upper Pivot Weldment		70.5	30.0
Balance of Parts		206.6	50.0
Hydraulic Panel	2	28.0	28.0
Hook	2	54.0	60.0
Hook Adapter	2	33.0	Eliminate
Structural Frame	2	355.0	130.0
Subtotal		919.0	392.0
2 Arms and Frame		1,838.0	784.0
AAELSS Electronics and Wiring	1	45.0	30.0
Airframe Hydraulic	1	42.0	40.0
SRD-84 and Wiring	1	54.0	50.0
Slings	1	20.0	20.0
Total		1,999.0	924.0

*NOTE: AAELSS II installation weight would be approximately 1,750 lb (i.e., 1,999 lb less weight of hooks, adapters, wiring, and slings) on any aircraft configured for dual-suspension external sling loads.

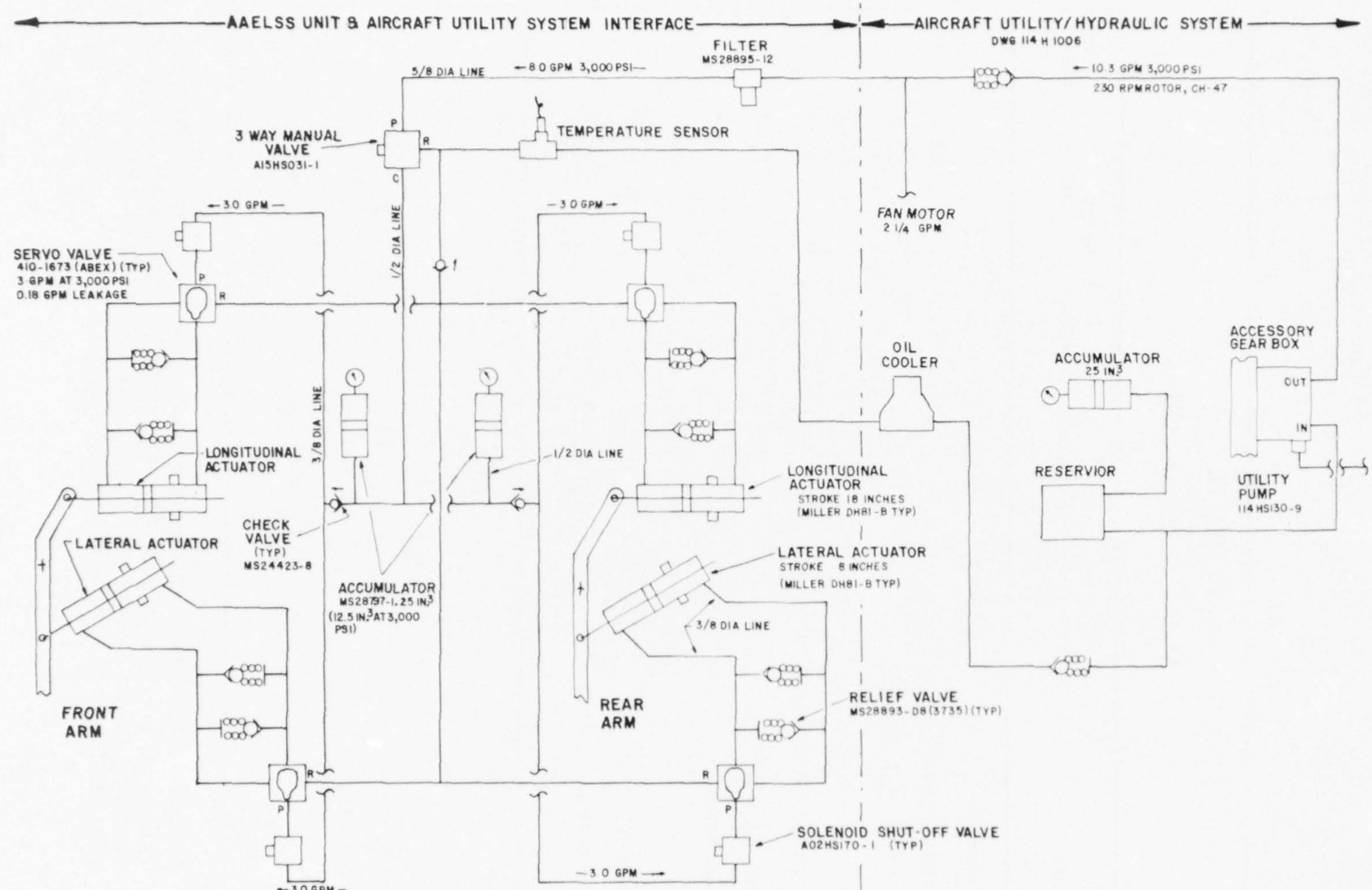


FIGURE 24. SCHEMATIC, HYDRAULIC SYSTEM, ACTIVE-ARM EXTERNAL LOAD STABILIZATION SYSTEM

places both flow and heat dissipation demands on the system. Neither of these requirements proved to be a problem in the AAELSS flight demonstration, since both were well within system capabilities. Figure 24 presents a schematic of the composite hydraulic system, with the aircraft utility supply shown on the right, system interface in the top center, and individual front and rear arm AAELSS components shown at the bottom. Appropriate flow rates, capacities, and dimensions, etc., are annotated on the figure.

The four AAELSS servoactuator valves are each rated at 3 gallons per minute (gpm) peak output, and thus establish maximum flow at the actuator. To average the system requirements and thereby conserve flow, 12.5-in.^{3} oil volume accumulators were installed on each unit. These accumulators provided slightly more than the 8-in.^{3} design volume required for each arm, and permitted an average flow rate of 2 gpm per actuator, or 8 gpm for the entire system with all four actuators moving at maximum rate. This 8 gpm flow is well below the 11 gpm system utility pump capacity, even with the 2.25 gpm utility system cooler operating continuously.

Heat rejection associated with 8 gpm peak flow into AAELSS is 610 Btu per minute, which is approximately equivalent to the utility cooler rated capacity. On the aircraft, utility cooling capacity was never taxed, since all four actuators seldom operated at peak rates simultaneously. In addition, hydraulic temperature was reduced substantially by convective cooling of exposed interface pressure and return lines on the aircraft bottom and fuselage interior as shown in Figures 3 and 14. System operating temperature, measured with a thermocouple adjacent to the utility pump (and monitored continuously in the cockpit throughout the test), averaged between 100° and 130°F in hover and forward flight, well below permissible system limits.

2.7.2 Failure Protection Precautions

Care was taken throughout the flight and ground test programs to avoid hydraulic temperatures above 190°F in order to protect seals and other component parts in both the aircraft and AAELSS. This was no problem in the flight program, as indicated above. In fact, quite the opposite was true in that the actuators had a tendency to "weep" fluid during initial daily operation (at utility temperatures below 80°F), as the system was coming up to normal operating temperature conditions. Because of this tendency, the arms were exercised over the pit (described earlier) as a preflight precaution to prevent later leakage, just prior to engine start and liftoff to ensure adequate utility system temperature for AAELSS operation in flight.

A second major precaution followed in operation of the hydraulic system was a continuous check of the system's fluid level, as indicated by the utility reservior piston extension on the helicopter. Because the aircraft's ground steering, brakes, and personnel hoist functions were all utility system powered, it was extremely important to prevent depletion of system fluid levels and risk potential damage in these areas as a result. The utility interface connection for AAELSS was configured with a check valve in the return line, and a three-way manual shut-off valve accessible to the flight engineer-observer, to prevent excessive loss of utility system fluid in the event of a major leak or other problem on either of the AAELSS units beneath the aircraft.

2.7.3 Hydraulic System Components

Figure 24 identifies the major AAELSS and utility interface components by part number, and Figure 25 shows how the various control valves and associated plumbing elements were arranged on the individual unit hydraulic panels. Most are MS items or components used somewhere on the CH-47, such as the solenoid and servo valve elements, which are identical to aircraft SAS link parts except for flow ratings. The bypass valve that functions to short-circuit cylinder ports when the system is off (as described in Figure 5) is built in as an integral part of the servo valve body. In a developed production system, all of these items (including the required relief valves) could be incorporated in a single manifold for each actuator.

After determining that no readily available Military-type hydraulic actuators met size and stroke requirements for AAELSS, commercial cylinders manufactured by Miller, Inc were selected to do the job. Actuators of this type have been extensively used in structural test applications at Boeing Vertol for a number of years, having been found to be both reliable and relatively inexpensive. The fatigue life margins for the AAELSS actuators were established during the "Bench" test program discussed later.

All actuator cylinders were adapted to use aircraft-type Teflon-impregnated/Dacron spherical rod end bearings, and the Teflon-lined plain bearings discussed earlier for trunnion mounting. The lateral actuator was run with a fixed trunnion, and was shimmed at the rod end to eliminate side pressure on the rod end head seals. The longitudinal actuator was of simpler design, with a gimballed trunnion mounting structure.

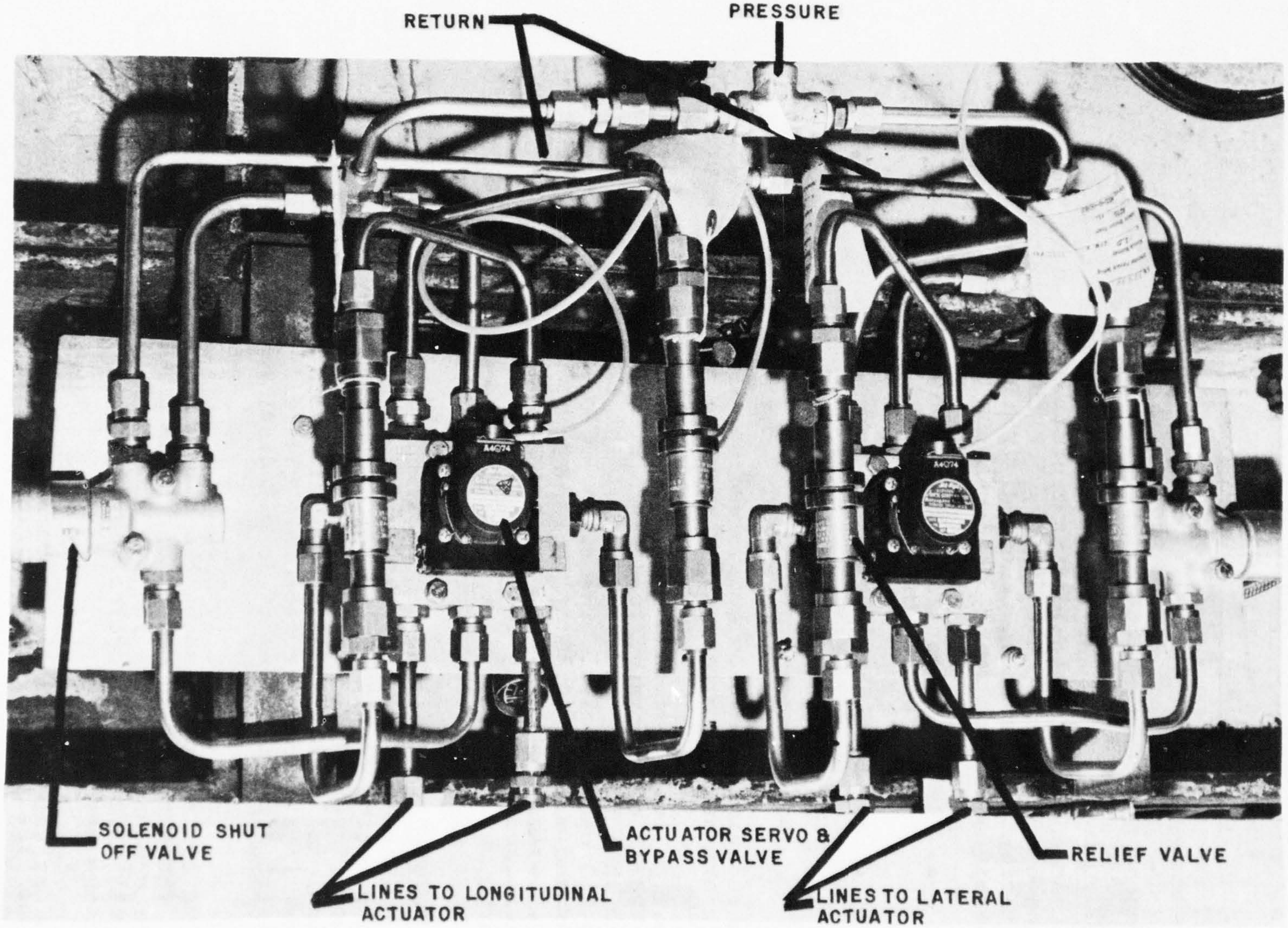


FIGURE 25. INDIVIDUAL AAELSS UNIT HYDRAULIC PANEL

3.0 "BENCH" QUALIFICATION TEST

3.1 TEST OBJECTIVES AND PROCEDURE

After fabrication, a single AAELSS arm assembly was mounted on the HLH cargo hoist tower (shown in Figure 26) to undergo a "bench" structural test qualification. Objectives of the tower test were to establish the structural integrity, safety aspects, and functional suitability of the AAELSS design, while undergoing steady and cyclic loading typical of flight. Within the area of functional suitability, "critical component" wear characteristics were to be assessed. These "critical components" identified at the start of the AAELSS II design were:

- The AAELSS central cable tension member (fabricated from a section of HLH cargo hoist cable)
- The bell-shaped guidance ferrule
- The Teflon/Dacron lined bearings supporting the arm and actuators

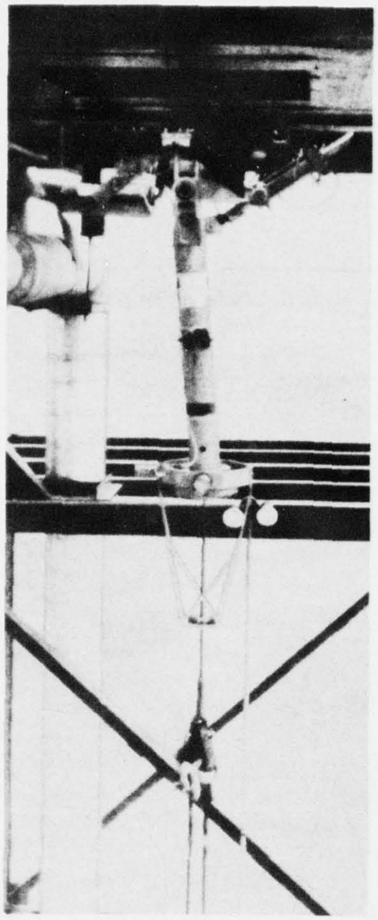
An additional test objective was to assess the performance of the arm automatic retraction sequence and uplock mechanism.

Test payloads suspended from the arm included a preliminary 4,000-lb concentrated load oscillated for 7,300 cable cycles, and then finally a design payload of 12,000 lb for an additional 14,900 cable cycles. The 12,000-lb payload represented an assumed maximum 60:40 split in arm load distribution for the 20,000-lb AAELSS design condition. Both of these loads were exercised by driving the longitudinal and lateral actuator servo valves with a direct sinusoidal command from a signal generator using the pattern indicated in Figure 27.

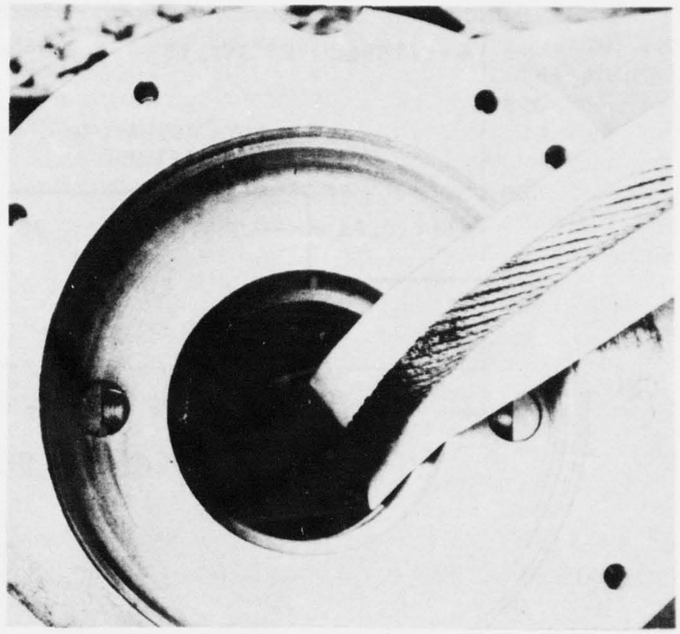
To start each loading sequence, the lateral actuator was oscillated at slightly above load natural frequency to minimize load motion for 10 cycles. (Long riser pendulum period was about 9 seconds.) This was followed by 18 cycles of longitudinal and lateral motion together, which forced the load to move in a triangular pattern. The loading sequence was completed with 10 cycles of longitudinal motion.

The entire operation took about 4 minutes to complete, and each load cycle imposed about two-thirds of the rated stall torque on the actuator in operation. This process produced 74 actuator cycles for every 100 cycles of the cable, and was repeated until 22,200 cable cycles were accomplished at the termination of the test.

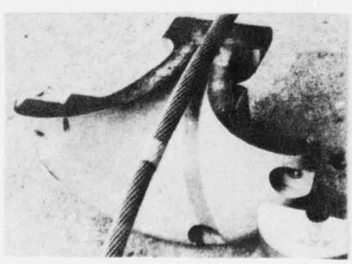
Before the tower test was completed, arm retraction tests were performed with the unit canted in order to permit full arm



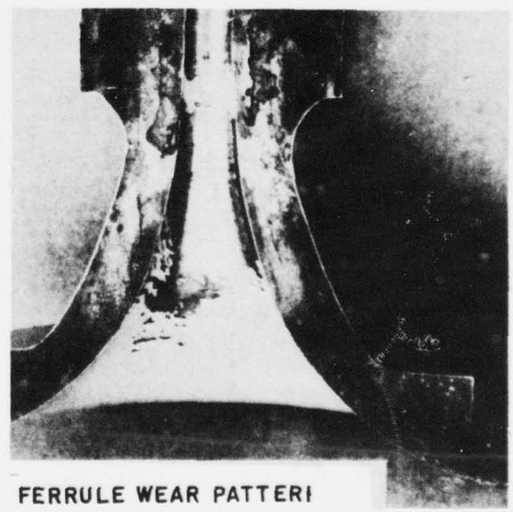
INSTALLATION ON TOWER



LOWER ARM WITH FERRULE REMOVED SHOWING CABLE

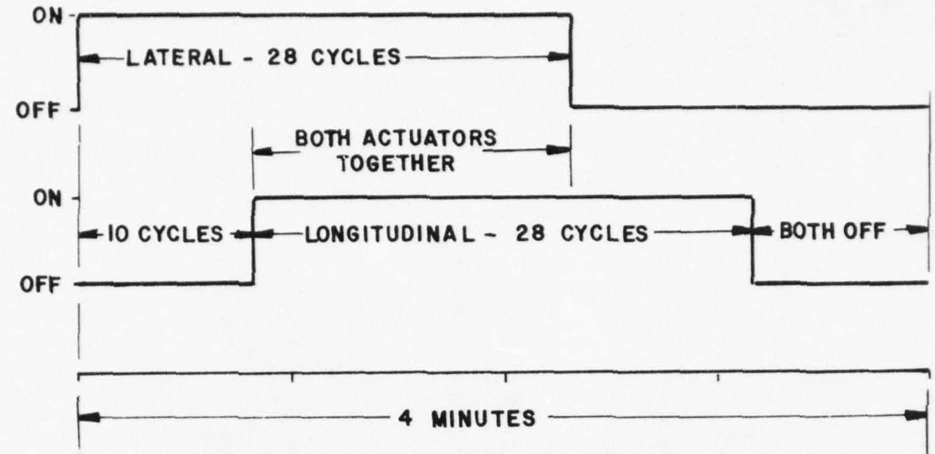


DISASSEMBLED FERRULE
AND CABLE

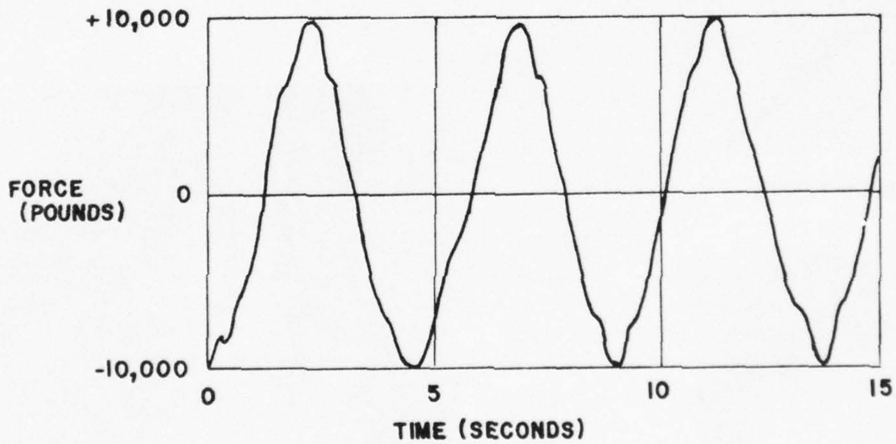


FERRULE WEAR PATTERI

FIGURE 26. AAELSS II CRITICAL COMPONENT WEAR FOR 22,000 CYCLE BENCH TEST



ACTUATOR OPERATING SEQUENCE



TYPICAL ACTUATOR LOAD

FIGURE 27. AAELSS II BENCH TEST LOADING

movement onto the uplock. The tower decking depth was such that full arm retraction was not possible until the structural attachment frames (similar to those later used on the aircraft) were tilted slightly. These tests indicated a need for several design changes, which are discussed later.

Following completion of tower testing, the cable tension member was removed and subjected to a successful 60,000-lb tensile proof loading in a specially guarded jig installed on a standard Universal Testing Machine (UTM).

3.2 "BENCH" TEST RESULTS

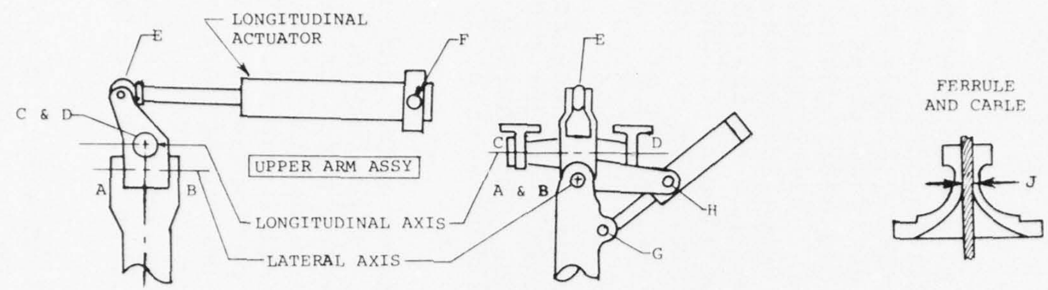
The wear measured on "critical component" elements at completion of the test and summarized in Table 4 was found to be almost negligible and well within expected limits. Figure 26 shows what the cable and ferrule looked like after posttest disassembly, and Figure 28 displays a typical bearing showing virtually no wear at the end of the test. All components demonstrated fatigue lives approximately 10 times longer than expected in the 10-hour flight program, which anticipated reaching stall torque levels about 20% of the time in flight. Even the most critically loaded items, the threads on the rod end bearings, demonstrated fatigue life far in excess of anticipated testing on the flight vehicle.

As shown in the table, the highest bearing wear occurred in the vertical plane at A and B due to high unit pressure from the actuator induced moment across the joint. The bearing condition, despite this play, was still excellent with no fretting or scoring or other faults noted.

The condition of the ferrule at test termination indicated only minor scrubbing of the inner surface about halfway down the bell mouth as shown on the lower right-hand photo in Figure 26. This wear pattern (which was later duplicated in the flight program) indicates that the lower half of the heavy ferrule structure is not necessary for satisfactory performance, and could therefore be removed to save weight. Some minor corrosion of the 4130 steel in the "polished" area of the ferrule indicated a necessity for changing the bellmouth material to either stainless or other low corrosion steel to prevent the problem in any production application.

During the retraction test, minor problems with the arm guidance cam location and operation of the uplatch were uncovered. It was determined that arm static weight was too great to operate the uplock mechanism manually prior to deployment. As a result, a special function was later incorporated into the AAELSS operation, permitting the arms to be lifted off the latches to relieve the load for manual unlocking before deployment.

TABLE 4. AAELSS II BENCH TEST CRITICAL ELEMENT WEAR



DIMENSIONAL CHANGE AFTER 22,200 CABLE CYCLES AND 16,400 ACTUATOR CYCLES

ITEM	POSITION	DIRECTION	CHANGE IN MEASUREMENT (INCHES)	COMMENTS
Bearing	A & B	Vertical	0.008	
	A & B	Horizontal	<0.001	
	C	All Radials	0.002-0.003	
	D		0.003	
	E & F		<0.001	
	G		<0.001	
	H		No data-damaged	
Cable	J	Radial	0.010 Reduced diameter	Cable wear marks were very minor ≥0.002 depth. Reduced diameter due to cable set.
Ferrule	J	Contour	<0.005	An optical comparator could not resolve any significant change. Corrosion did develop, and the metallurgist recommended corrosion resistant steels that did not cold-work harden.

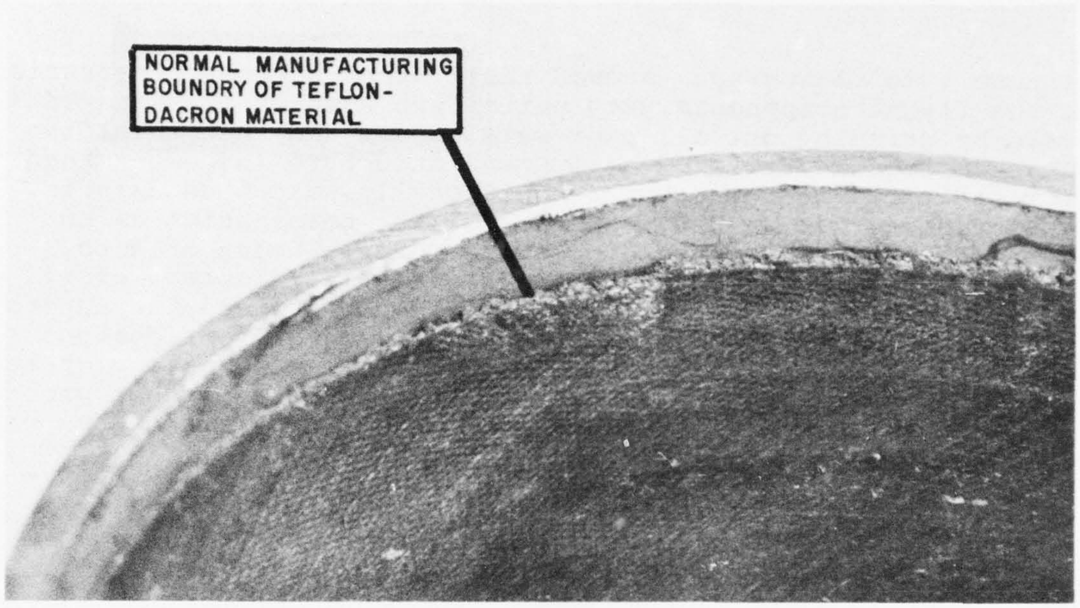


FIGURE 28. TEFLON/DACRON BEARING SURFACE, SHOWING NEGLIGIBLE WEAR (AFTER 16,400 CYCLES)

During the cycling test, a structural failure occurred in the lateral arm trunnion mount assembly lug where it was welded to the pivot block arm at position H shown in Table 4. The lug-to-arm weldment showed several areas of very poor weld penetration and porosity within the joint itself. The remaining unfailed lateral arm and two additional pivot block assemblies intended for the operational and flight programs were thoroughly checked with dye penetrant and radiographic (X-ray) methods to determine if similar problems existed.

Because some radiographs showed small areas of poor penetration on the flight components, both units were completely remanufactured by grinding out all poor weld areas, and then rewelding these as required to produce a sound structure (as determined from radiographic rechecks). Additionally, a canted 3/16-in. doubler plate was welded onto the arm/lug termination as an additional safety feature, to provide more weldment area to stiffen the joint and to reduce stresses in existing welds. One of these doublers is visible at the point where the lateral arm joins the actuator trunnion in Figure 14. The redesigned joint performed extremely well throughout the operational test and flight programs, and showed no evidence of any other problems when the units were inspected at the time testing was completed.

4.0 OPERATIONAL TEST OF FLIGHTWORTHY SYSTEM

4.1 OBJECTIVES AND PROCEDURE

After completion of "bench" testing, both flightworthy AAELSS units were mounted on the HLH tower for an "operational" test of the complete system with a 20,000-lb ballasted Milvan payload, supported on 37-ft risers (producing the 60-ft pendulum length later evaluated in flight test). Except for aircraft structural attachment frames, AAELSS components used in this final ground test duplicated those installed on the test aircraft one month later, as shown in Figure 29.

Test objective was to operate the various AAELSS elements as a system for the first time, and thereby eliminate anomalies and "bugs" before the start of the flight test. In addition to this functional objective, control law parameters were varied (using two gains per axis and 5 to 7 lag time constants) to determine system pendular damping. The principal purpose of this testing was to establish an initial set of gains and time constants for the flight program.

Additional testing was aimed at demonstrating the elimination of hysteresis so prevalent with AAELSS I. This consisted of allowing the system to stabilize the Milvan in gusty wind conditions, while measuring load excursions about a ground target.

4.2 TEST RESULTS

A typical time history of load excitation (with the signal generator described in the "bench" test), followed by AAELSS on damping, is shown in Figure 30. The method of exciting the load was necessarily different from the approach later used on the test aircraft, but when the arm driving signals were removed, AAELSS operated in its normal damping mode to attenuate load motion. Test results were very linear on the tower, as shown in the "pendulum" angle time history. Later testing on the flight vehicle, with various linear and rotational airframe modes mixed in, was somewhat more difficult to interpret, but the same high damping levels were measured on the aircraft as demonstrated on the tower.

Figure 31 summarizes longitudinal and lateral axis variations in pendular damping measured for different lag shaping time constants. Test results are compared with the 25% of critical damping design objective, and MIL SPEC H-8501A requirement for 5.5% damping under IFR conditions. A comparison of tower and aircraft AAELSS damping results is presented in Section 5.

Tower tests showed conclusively that the AAELSS II sensor package eliminated limit cycle oscillations (at the basic sling frequency) associated with hysteresis in the earlier system. In quartering crosswind conditions gusting to 25 kn, AAELSS II was shown to hold load position within ±1.5 in. longitudinally, and ±3.0 in. laterally. In 10 kn winds, no longitudinal motion was present and lateral box movement was only ±0.5 in.

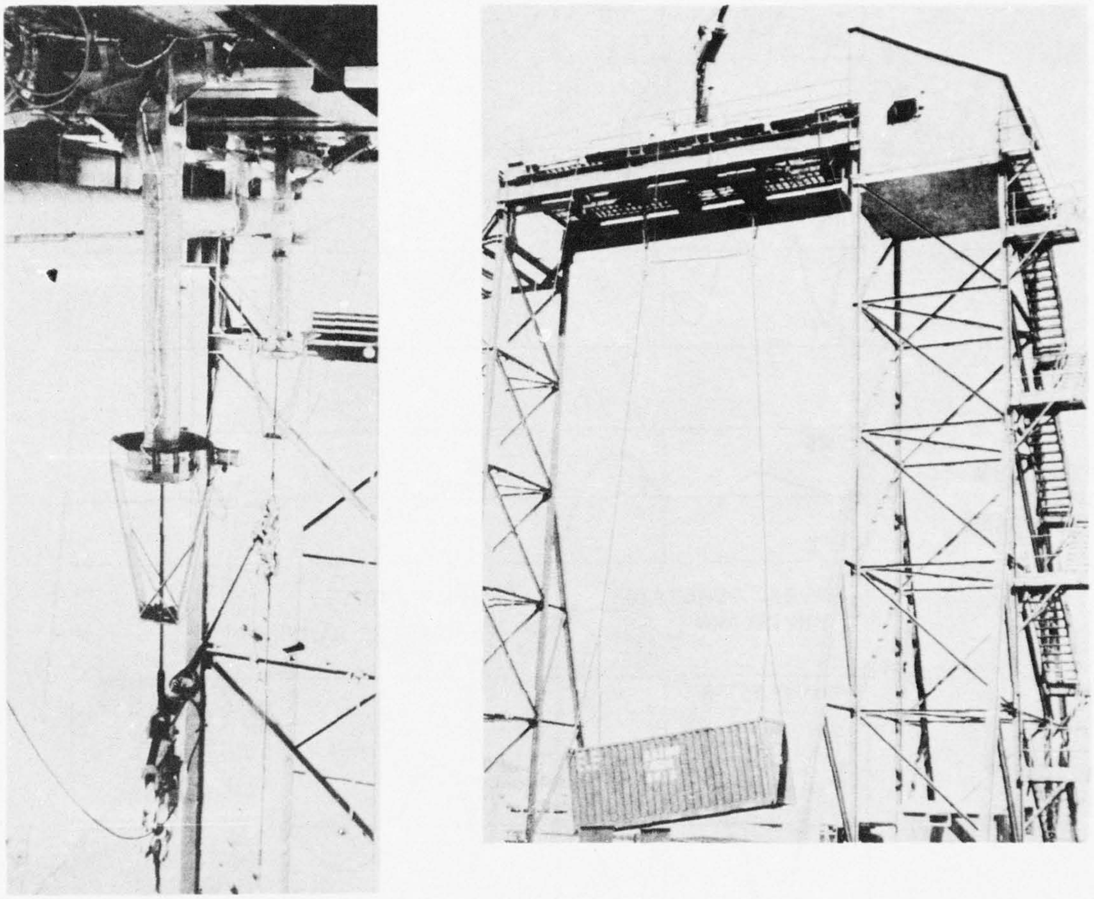
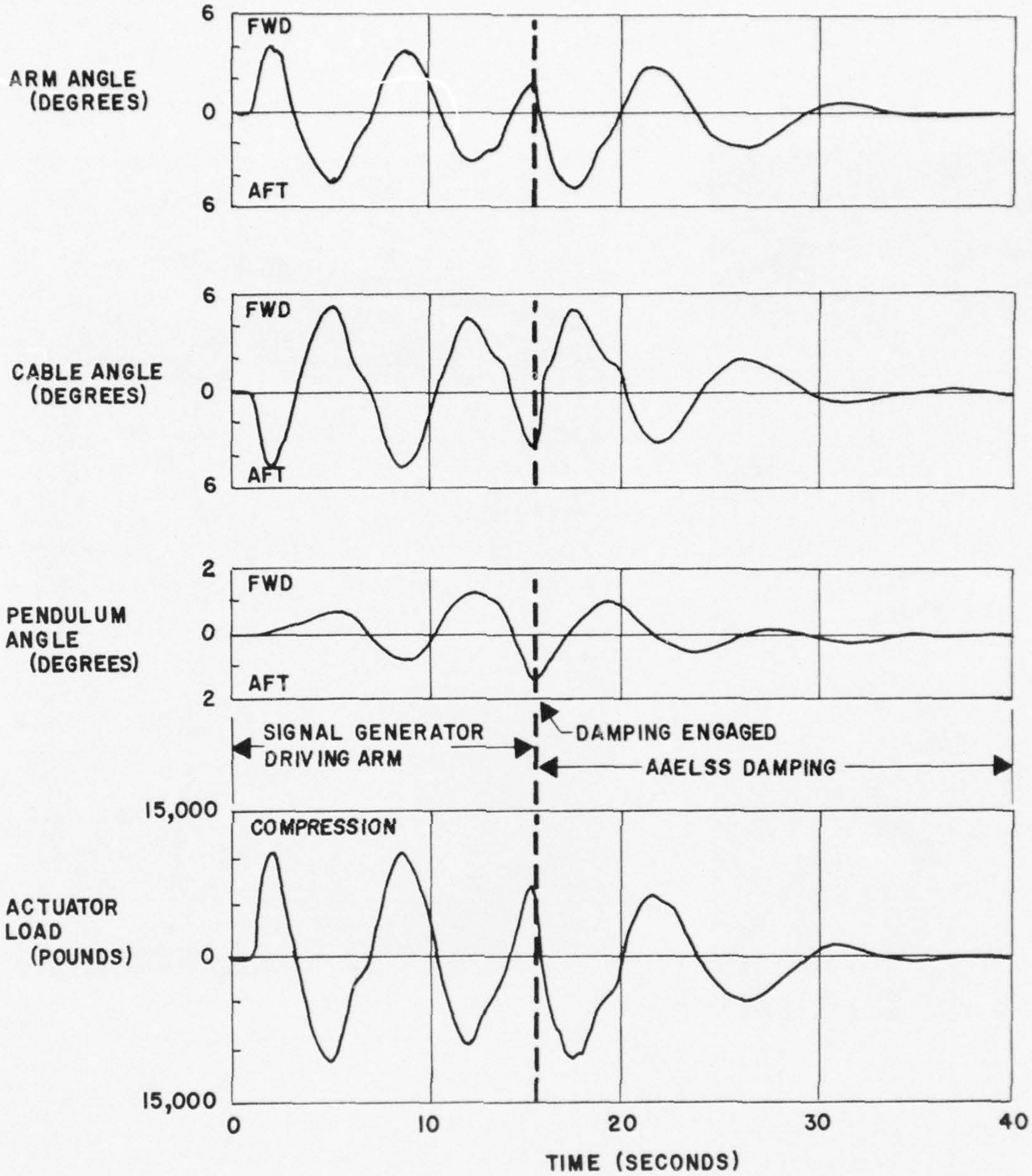


FIGURE 29. OPERATIONAL TEST ON HLH CARGO-HANDLING TOWER

LONGITUDINAL AXIS PARAMETERS



MILVAN GROSS WEIGHT 20,000 LB
AAELSS GAIN 20 DEG/DEG
LAG TIME CONSTANT 3.6 SEC
WASHOUT TIME CONSTANT 15.0 SEC

SLING 37-FT RISER
(60-FT PENDULUM)
FRONT ARM DATA

FIGURE 30. TOWER DYNAMIC STABILITY TEST

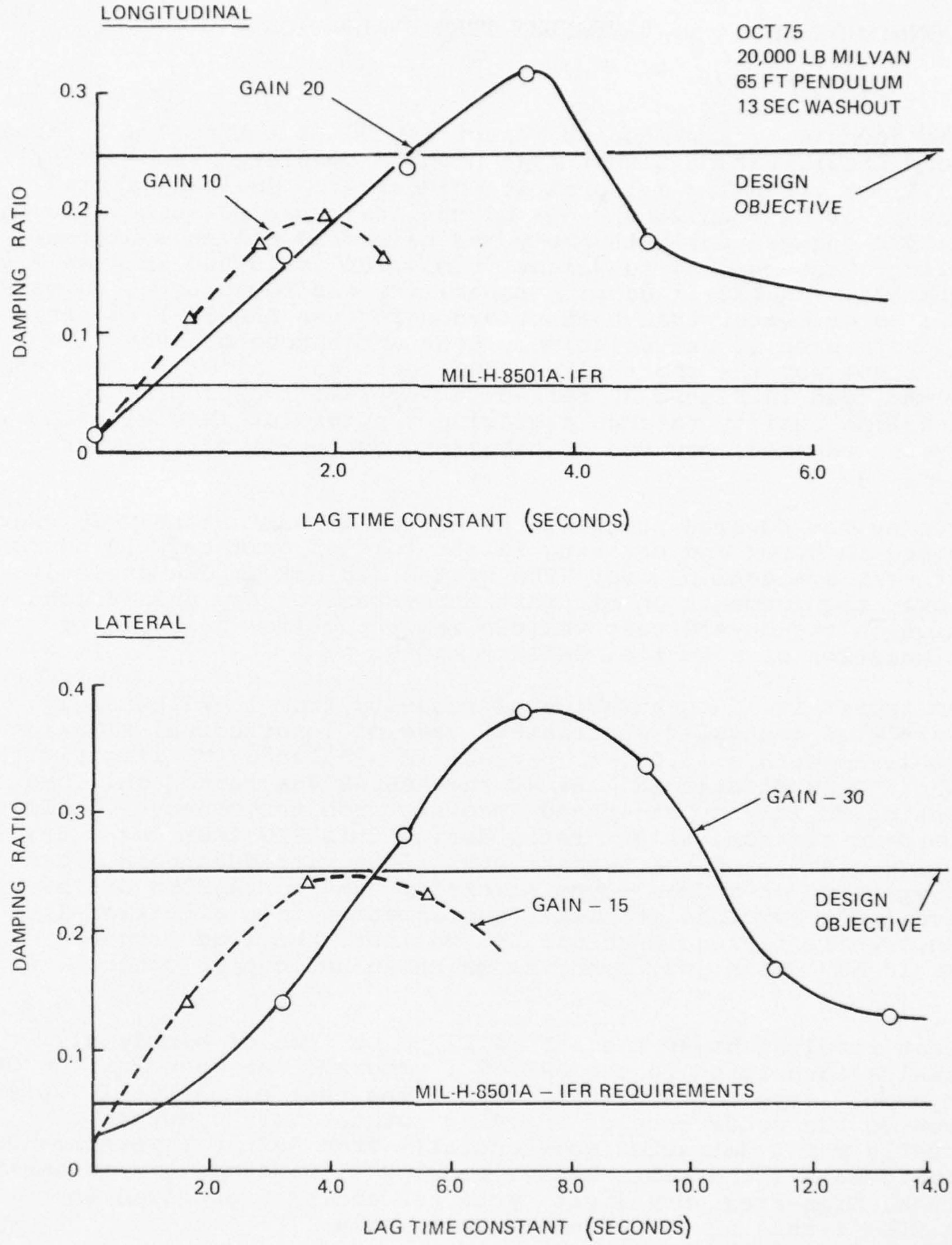


FIGURE 31. BOEING VERTOL OPERATIONAL TEST HLH CARGO TEST TOWER

5.0 FLIGHT TEST EVALUATION

5.1 SUMMARY

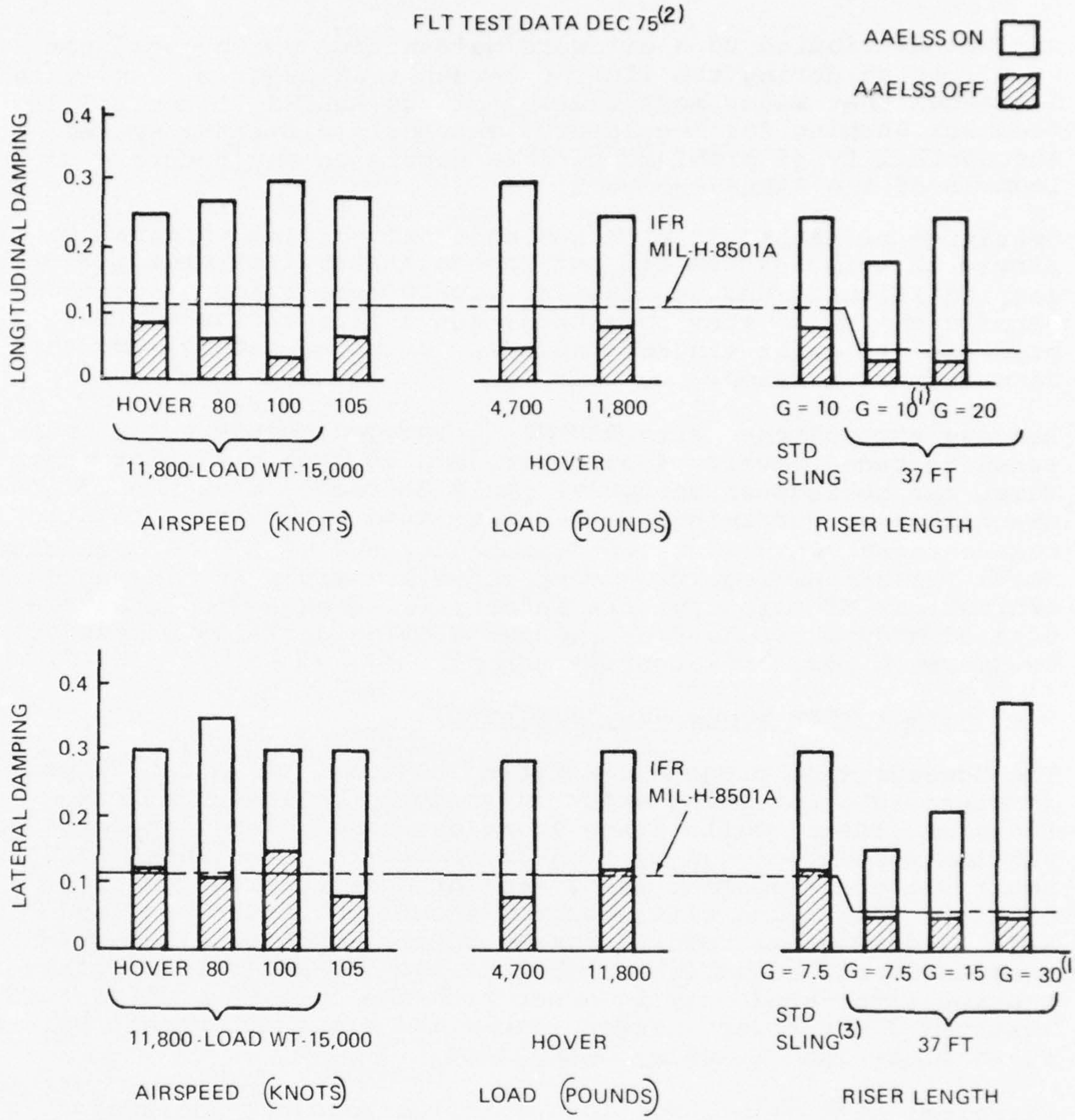
The joint U.S. Army/Boeing Vertol AAELSS II Active Arm External Load Stabilization flight test program completed in December 1975 met virtually all pretest objectives. Desired damping levels of between 25 and 30% of critical were measured with the AAELSS engaged for both empty and ballasted Milvan container sling loads ranging in weight from 4,700 to 15,000 lb (see Figure 32). AAELSS II damping capability was found to be comparable to or better than that recorded for the AAELSS I, described in Reference 1, and relatively constant throughout the flight envelope for the short-sling configuration. Pilot HQR scores summarized in Figure 32 reflect an overall improvement in handling quality ratings averaging 2 points or more with the system engaged, because of the improved levels of pendular damping.

During the Edwards program, the AAELSS II was extensively exercised in hover and cruising flight for approximately 14 hours of test evaluation time. The system did not impose excessive power requirements on aircraft subsystems or any unsafe condition on the CH-47C test vehicle resulting from failures or simulation of potential failure modes.

An impressive demonstration of recovery from a deliberately initiated (but self-sustaining) case of longitudinal PIO was achieved with a 15,000-lb payload in simulated IMC flight with the AAELSS disengaged. After the AAELSS was turned on, load motion rapidly subsided and recovery from the maneuver followed. Load-to-airframe weight ratio during this PIO test was 0.55, which was one of the highest ever flown with dual-point load suspension on a CH-47-type aircraft. Had the AAELSS not been available for load stability augmentation in a situation like this while flying in actual IMC weather, the load probably would have been jettisoned to maintain helicopter control.

Test results showed the AAELSS II to be free of nearly all faults identified in the AAELSS I program. Adequate sizing of hydraulic cylinder capacity (two times that of AAELSS I), prevented the occurrence of annoying torque limited actuator stalls which detracted substantially from AAELSS I performance. Improved arm and cable sensor modules eliminated the low amplitude, high-frequency limit cycle tendencies identified in AAELSS I and caused by sensor hysteresis.

A long-period, lateral-axis, limit-cycle oscillation also found in the earlier system was not, however, completely eliminated with the AAELSS II. This problem was most noticeable in forward flight where it occurred randomly on the front AAELSS arm only,



TYPICAL HQR RATING STANDARD SLING		
	AAELSS OFF	AAELSS ON
HOVER	5-6	3-4
FWD FLT	4-5	3

G CONTROLLER GAIN – DEG ARM/DEG CABLE
(1) HLH TOWER OPERATIONAL TEST
(2) CH-47C SN 15858 @ EAFB, CALIF WITH 8x8x20 FT MILVAN
(3) 11 FT FWD AND 8 FT AFT SLING – NO RISER

FIGURE 32. AAELSS II DAMPING AND HANDLING QUALITIES RATING SUMMARY

and was attributed to a hardware malfunction which could not be corrected during the limited 2-week test program. Analysis has shown that minor modification of the AAELSS II control law feedback shaping for the lateral axis would eliminate system susceptibility of problems of this nature on any future development of the AAELSS concept.

Operation of AAELSS II with a single axis or arm inoperative proved that the system did not create instability or other problems in flight. Reduced damping levels were evident when compared with full system operation, but a lateral instability predicted to exist (in Reference 2), with one lateral arm shut down did not develop.

Testing accomplished with AAELSS II engaged occasionally indicated degraded levels of pendular damping when the pilot maneuvered the helicopter abruptly. This decrease in augmented load stability was determined to be associated with aircraft attitude changes, which were interpreted by the AAELSS as "pendulum" angle variations requiring corrective arm movement. Sling load excitations of this type can be eliminated by a simple subtraction of body attitude from the pendulum control law commands, to decouple load and airframe motion.

5.2 FLIGHT TEST SCOPE AND OBJECTIVES

The Edwards test program was set up to evaluate AAELSS II performance in stabilizing empty and heavily ballasted Milvan container loads, while using short and long riser sling suspension systems of the type shown in Figure 33. The "standard" short sling arrangement installed for most testing consisted of 11-ft dual nylon slings on the front end of the box, and 8-ft slings on the rear, arranged in the inverted "vee" suspension described earlier in Figure 33. An alternate configuration (evaluated only in hover with the ballasted Milvan) inserted 37-ft risers between hooks and sling attachment points to simulate load winching operations.

Principal test objectives for the flight program included:

1. Evaluation of longitudinal PIO in simulated IMC flight with significant ratio of load to airframe weight (maximum considered practical within the limits of aircraft OGE hover takeoff performance).

2. Demonstration of the following, while carrying ballasted and empty Milvan payloads:

    - Pendular damping ratios equal to or better than AAELSS I ($\geq \zeta = 0.25$)

STANDARD SHORT SLING (11-FT FWD AND 8-FT AFT)
TEST CONFIGURATION WITH AAELSS
SYSTEM OPERATING

LONG SLING (37-FT RISER)
HOVER CONFIGURATION

FIGURE 33. AAELSS II FLIGHT TEST ON CH-47 C HELICOPTER

- Freedom from limit cycle or other lightly damped oscillations, especially those resulting from sensor hysteresis of the type identified in the earlier AAELSS

- Hydraulic cylinder capacity adequate to prevent frequent actuator stalls under heavy loading conditions

- Operation without imposing excessive hydraulic or electrical power requirements on aircraft subsystems, or unsafe conditions on the helicopter

3. Exploration of dynamic stability conditions not investigated in the AAELSS I tests, including operation with a single-arm axis inoperative.

4. Demonstration of the feasibility of using AAELSS II components suitable for application with an HLH-type winchable cable system including arm, ferrule, cable tension member, and cable cage sensor along with conventional fixed cargo slings.

5.3 TEST PROGRAM

This section of the report briefly describes test equipment, test instrumentation, the preflight safety of flight review, and the test procedure and conditions. A complete description of the AAELSS installation and how it works has already been presented in Sections 1.3 and 2.0.

5.3.1 Test Equipment

All testing was accomplished on a standard CH-47C aircraft configured with a cruise guide indicator (CGI) and an instrumentation package for measuring aircraft and sling load response characteristics. Dual SAS operation was used throughout the program; however, the airspeed and pitch attitude hold feature provided by the PSAS was disengaged at times because of a malfunction.

The cargo hooks used with the AAELSS II demonstration were modified CH-54B Eastern Rotorcraft C-250 devices, which are qualified for operation at 30,000 lb loads. These hooks are similar to those used in the tandem hook SRD-84R1 and R2 programs (References 4 and 5). Internal load sensing schemes are virtually the same for both hooks, but the C-250 has a 50% greater load capacity and is slightly larger in overall size.

SRD-84 control electronics and harness systems, incorporating the "auto jettison" feature described earlier, were installed as part of the AAELSS test setup. Hook release modes included manual and emergency electrical activation capability, and a backup Teleflex cable operated mechanical emergency release system located in front of the engineer/observer station at the cargo hatch.

The flight engineer/observer crew station is pictured in Figure 34. Shown are the AAELSS electronic control modules, which permitted individual axis AAELSS operation, and a panel of decade boxes for in-flight adjustment of control law parameters. The small switching box shown in the lower right-hand corner of the photo was used to retract either arm separately for test or emergency purposes without the use of AC electrical power (controls provided the pilot utilized both DC and AC power to effect automatic simultaneous retraction of both arms).

Throughout the test program, the flight engineer/observer occupied the crew station, shown in Figure 34 (located behind the cargo hatch), and watched the performance of the forward AAELSS arm. A second observer station was designated in front of the hatch. This crewman observed the aft arm and was responsible for activating the manual emergency load jettison system.

A pilot's AAELSS control panel was mounted in the cockpit on the left-hand top corner of the center pedestal (Figure 35). The copilot normally operated the system through the AAELSS hydraulic (on-off) switch after engaging AC and DC circuit breakers. Arm uplock condition lights indicating the retraction status of both arms are installed on the cockpit control panel, along with the "retract/operate" switch mentioned above.

In addition to the cockpit AAELSS panel just described, the copilot also had a separate "hardover injection box" to control the input of simulated AAELSS hardover failures for each axis.

5.3.2 Test Instrumentation

The AAELSS test instrumentation package consisted of an oscillograph recorder and appropriate sensor-transducers for measuring aircraft rates, attitudes, linear accelerations, cockpit control positions, and airspeed, along with AAELSS parameters. Among these were cable, arm, and pendulum angular positions, and selected actuator and cable loads. Also recorded were CGI readings, and timing and event mark data.

Test parameter range and sensitivity information is presented in Table 5. Also shown is a list of cockpit data associated with the test and available to the pilot, including utility hydraulic system temperature, arm pendulum angles for limiting test maneuver buildup, and CGI readout. Arrangement of cockpit instrumentation is detailed in Figure 35.

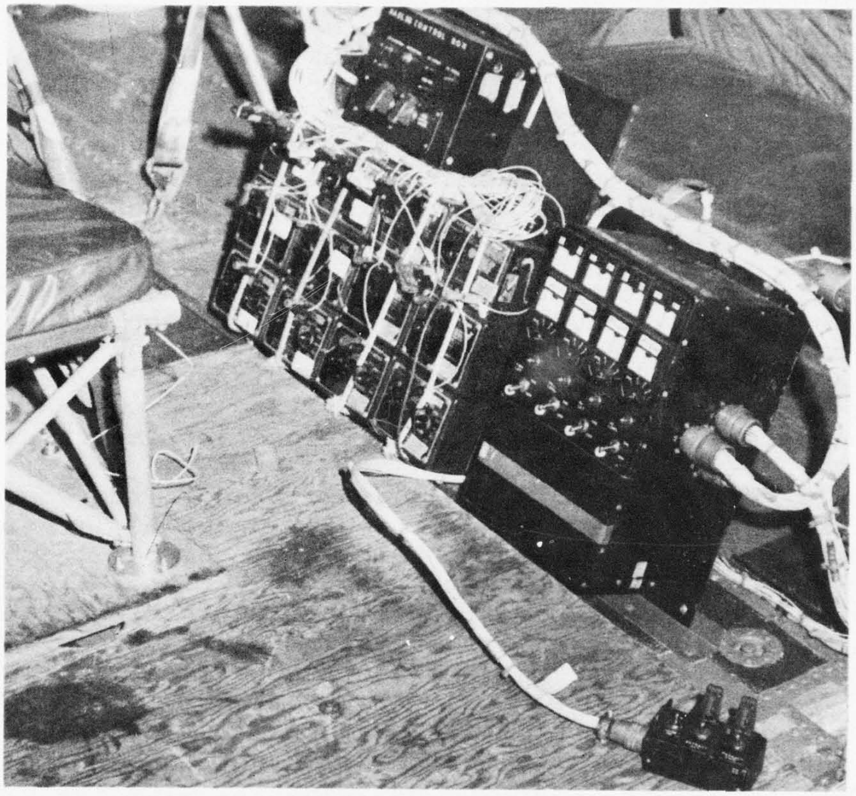


FIGURE 34. FLIGHT ENGINEER / OBSERVER CREW STATION WITH AAELSS II CONTROL PANELS

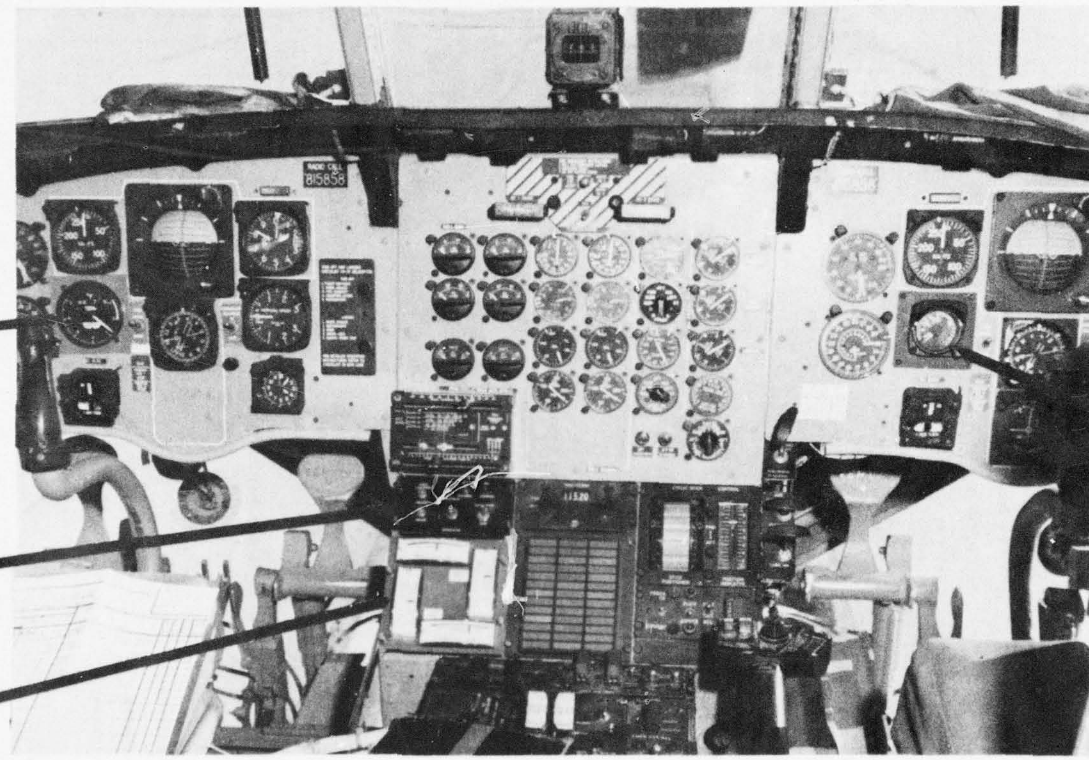


FIGURE 35. AAELSS II /CH-47C COCKPIT INSTRUMENTATION AND PILOT'S CONTROL PANEL LAYOUT

TABLE 5

AAELSS II DATA PARAMETER LIST FOR TEST INSTRUMENTATION
(EDWARDS AFB EVALUATION - DECEMBER 1975)

ITEMS	PARAMETER	RANGE	SENSITIVITY	OSCILLOGRAPH	COCKPIT
1	Fwd Actuator Long Load	±18,000 lb	10,000 lbs/in.	X	
2	Fwd Actuator Latl Load	±18,000 lb	10,000 lbs/in.	X	
3	Fwd Cable Riser	30,000 lb	15,000 lbs/in.	X	
4	Aft Cable Riser	30,000 lb	15,000 lbs/in.	X	
5	Fwd Long Arm Position	+60, -90 deg	20 deg/in.	X	
6	Fwd Long Cable Position	±45 deg	20 deg/in.	X	
7	Fwd Long Pendulum Position	+60, -90 deg	20 deg/in.	X	
8	Fwd Long Load Position	±30 deg			X
9	Fwd Latl Arm Position	±30 deg	20 deg/in.	X	
10	Fwd Latl Cable Position	±45 deg	20 deg/in.	X	
11	Fwd Latl Pendulum Position	±45 deg	20 deg/in.		X
12	Fwd Latl Load Position	±30 deg			
13	Aft Long Arm Position	+90, -60 deg	20 deg/in.	X	
14	Aft Long Cable Position	±45 deg	20 deg/in.	X	
15	Aft Long Load Position	±30 deg			X
16	Aft Latl Arm Position	±30 deg	20 deg/in.	X	
17	Aft Latl Cable Position	±45 deg	20 deg/in.	X	
18	Aft Latl Load Position	±30 deg			X
19	AAELSS Hydraulic Oil Out Temp	300°F			X
20	Long Stick Position	6'5"	3.12 Equiv Stick Motion	X	
21	Latl Stick Position	4.18"	2.1" Equiv Stick Motion	X	
22	Dir Pedal Position	3.60	2.0 in.	X	
23	Pitch Angle Position	±30 deg	20 deg/in.	X	
24	Roll Angle Position	±30 deg	20 deg/in.	X	
25	Yaw Angle Position	±160 deg	90 deg/in.	X	
26	Pitch Rate	±40 deg/sec	24 deg/sec	X	
27	Roll Rate	±40 deg/sec	25 deg/sec	X	
28	Yaw Rate	±40 deg/sec	20 deg/sec	X	
29	Long Accelerometer	±2G	1 G/in.	X	
30	Latl Accelerometer	±2G	1 G/in.	X	
31	Vert Accelerometer	+3 -1G	1 G/in.	X	
32	Airspeed	13.52 in H_2O	6.7 in/in.	X	X
33	Cruise Guide	150%	100%/in.	X	X
34	Event			X	X
35	Elapsed Time (OSC Timing Lines)			X	X
36	1/Rev			X	
37	Trim Wheel (Longitudinal Stick Position)				X

5.3.3 Safety-of-Flight Review

Prior to the start of flight testing, an in-depth safety-of-flight (SOF) review was conducted at Edwards AFB by AVSCOM Flight Standards personnel, assisted by members of the Boeing Vertol-U.S. Army AEFA test and management teams. Information presented included a description of the system and its operating principles. AAELSS structural design had been reviewed several weeks earlier by AVSCOM stress engineers, and at the SOF meeting the hydraulic, electrical, and SRD-84 hook systems were covered in depth. A safety analysis conducted by Boeing Vertol and a listing of potential hazards associated with AAELSS operation (and methods of avoiding these hazards) were discussed.

A proposed flight envelope for AAELSS II testing was presented during the SOF review. This envelope is illustrated in the Figure 36 payload/speed limit chart. The diagram includes a speed boundary beyond which "auto jettison" hook release is required to prevent light Milvan payloads from hitting the aircraft after failure of the critical forward hook or sling. Vertical lines shown in the figure represent estimated NRP power limited speeds with a 100 ft^2 (fe) Milvan sling load at sea level and 4000 ft altitude.

At the top of the chart is a curve representing an expected degradation in longitudinal control sensitivity (of 25%) subsequent to failure of a fully loaded Milvan sling or hook suspension member (and retention of the load by the other arm). From the figure it is obvious that aircraft longitudinal control is not in question after suspension failure, for any practical payload usable by the test aircraft.

Two other curves shown on the diagram represented "ball park" estimates of expected potential maximum test speeds as limited by Milvan unaugmented directional stability, and AAELSS simulated hardover failure recovery maneuvering. The stars indicating maximum speeds later attained in the AAELSS II test program showed both of these limits to be conservative. This improved performance is attributed to the <u>shorter</u> AAELSS II inverted "Y" suspension, which improved inherent basic sling load directional stability appreciably, as will be shown later.

As a result of the SOF review, AVSCOM released the aircraft for flight to 110 kn with a maximum payload of 15,000 lb (based on OGE performance with sufficient fuel for a reasonable test period), and 90 kn maximum with the empty Milvan. As will be shown later, the empty Milvan was only flown to 80 kn because of the abbreviated nature of the test program (no stability limit was reached); and with the 15,000 lb payload, 105 kn represented the maximum power limited speed attainable.

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ACTIVE ARM (EXTERNAL CARGO) STABILIZATION SYSTEM FLIGHT DEMONST--ETC(U)
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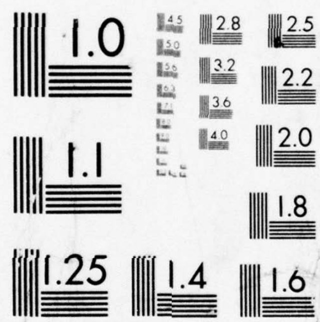
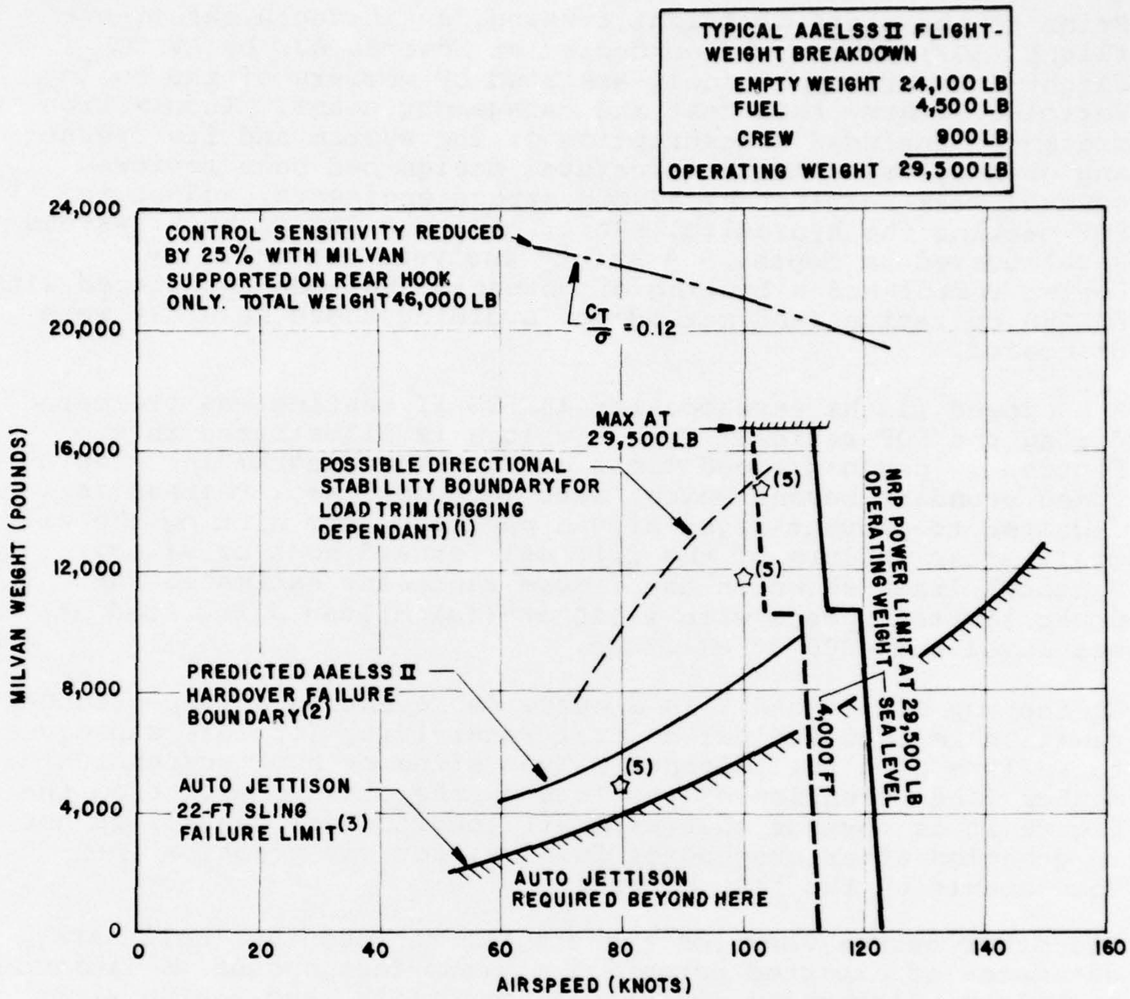


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



NOTES:

1. BASED ON EARLIER INVERTED "Y" TESTING WITH LIMIT CYCLE FOR LATERAL OSCILLATION ≈ ± 15 DEGREES
2. BASED ON ADJUSTED AAELSS I FLIGHT TEST DATA CORRECTED FOR AAELSS II INCREASE IN STALL TORQUE
3. BASED ON FARNBOROUGH (RAE) WIND TUNNEL DATA & THEORETICAL DYNAMIC ANALYSIS PERFORMED FOR SRD-84 PROGRAM
4. BOX fe 100 FT^2, AAELSS fe CACULATED = 17 FT^2
5. ☆ MAX AIRSPEED ACHIEVED IN AAELSS II TEST PROGRAM

FIGURE 36. AAELSS II FLIGHT TEST DEMONSTRATION ENVELOPE - CH-47C

5.3.4 Test Procedure and Conditions

All flight testing accomplished with the AAELSS II was based on the OGE multi-engine hover performance criteria just mentioned. Added to this OGE requirement was a small additional torque margin (of 4 to 6%) for vertical maneuvering to arrest inertial load motion. Potential single engine emergency situations in hover required immediate load jettison. Sufficient IGE hover performance on the remaining engine was always available, enabling the helicopter to remain well above the load (because the multi-engine OGE requirement was more severe, and therefore controlled aircraft gross weight).

Prior to flight testing, the aircraft was rolled over a 12-ft deep pit and the arms were deployed as shown in Figure 37. Final system rigging and instrumentation calibrations were accomplished with the aircraft stationed on the pit. In addition, complete checkouts of all AAELSS associated systems were performed, including both electrical and mechanical hook jettison tests, and operation of AAELSS to verify damping performance with small single-point loads attached to the hooks. Before each test flight, the arms were exercised over the pit to reduce the probability of unexpected in-flight malfunction.

Along with these system tests, emergency retraction of the arms was demonstrated over the pit by using both the hydraulically powered aircraft personnel hoist system and a mechanical bomb hoist mounted in the rear of the aircraft as a safety backup. With this backup arrangement, it was possible to retract the arms (even after the utility hydraulic system failed) with the AAELSS completely inoperative.

Initial instrumentation and functional checkout flights (with arms retracted, and then deployed) verified proper operation of the AAELSS and SRD-84 hook systems, using concentrated single-point loads varying in weight from 700 to 1,200 lb on both hooks. Typically, flight testing with the Milvan was started in hover and then progressed into forward flight, employing normal buildup techniques to ensure safety.

In the hover phase, AAELSS control law shaping time constants and gain settings were varied to determine which produced the best damping and pilot HQR scores. With the optimum parameters selected in hover, forward flight data points were set up where the following items were evaluated at each airspeed, and in the order listed:

- Baseline sling load damping with the AAELSS off was determined by measuring the load response to aircraft excitations (in the longitudinal, lateral, and directional axes) at the load natural frequency

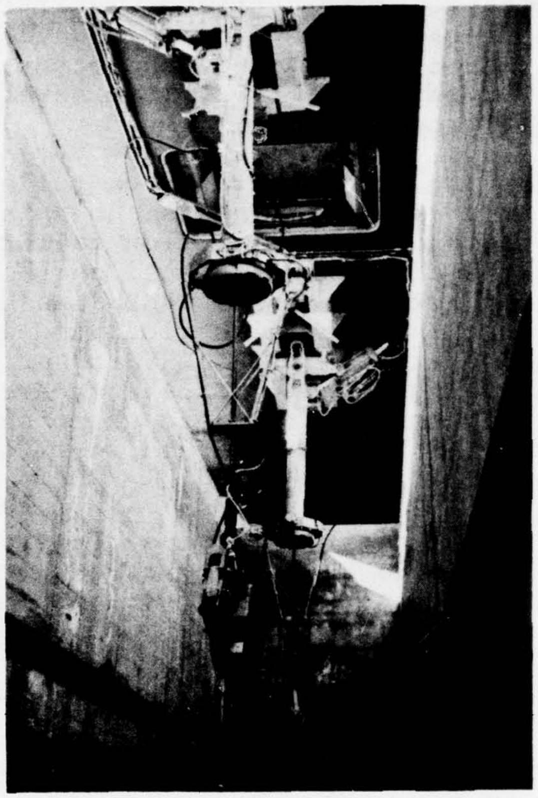


FIGURE 37. AAELSSII ARMS DEPLOYED FOR FUNCTIONAL CHECKOUT OVER PIT

was checked first. At no time was testing planned to continue beyond the point at which the load began to display unstable or lightly damped stability characteristics. This procedure was established to ensure the existance of stable load conditions in the event that one or more AAELSS axes failed inadvertently during subsequent "AAELSS on" testing.

In the actual buildup tests conducted, load lateral/directional stability never became a limiting factor, and maximum speeds flown were dictated by other considerations.

- Aircraft/load response to simulated AAELSS hardover and go-dead situations was assessed after "AAELSS off" testing. Single-axis, single-arm operation was also evaluated from the standpoint of stability and safety. Neither the hardover, nor single axis, nor arm operation proved to be a limit to the test envelope.

- Damping with the AAELSS on was determined next, with the system off initially during the aircraft excitation, and then on. The system was engaged when the copilot turned the AAELSS hydraulic switch on. HQR assessments for these dynamic stability runs were made with the pilot in the loop as AAELSS damped the load, and with the pilot out of the loop as much as possible for recovery.

  Dynamic stability testing was followed by a series of typical mission-oriented maneuvers, including turns, precision load shuttle/ placement tasks over ground target grids, and lift-off with offset loads. Where practical, maneuvers were evaluated with AAELSS off first, and then with AAELSS on augmentation assisting the pilot.

- Longitudinal PIO susceptibility was evaluated with the AAELSS off, then on, while in simulated IMC flight (with the pilot under the hood). To increase the realism of the test, the copilot on several occasions excited the load and then turned the aircraft over to the pilot for recovery on instruments only. In one case when severe PIO did develop, the pilot was unable to attenuate load motion and the AAELSS was turned on to terminate the maneuver.

PAYLOAD CONFIGURATION - When flown empty, Milvan loads with attachment slings and hardware, as shown in Figure 33, weighed approximately 4,700 lb. Three loaded configurations were evaluated with the ballast evenly distributed along the longitudinal Milvan centerline. These payloads weighed 10,000, 11,800, and 15,000 lb, respectively. Capability for varying payload was restricted to increments of about 1,800 lb each because of the type of ballast modules available.

FLIGHT LOG - The information presented in Table 6 summarizes all testing accomplished in the AAELSS II program. Aircraft and load configurations are shown on the left and the test condition and flight duration on the right. A total of 13.7 productive test hours were flown, and 288 data points taken. Two-hundred thirty-six of these pertained directly to evaluation of AAELSS performance.

On two flights, test objectives were not entirely met (X-2 and X-5). During the initial part of flight X-2, satisfactory performance margin was not available for maneuvering the long riser 15,000 lb load. Testing was discontinued and the payload readjusted to 10,000 lb. The problem was traced to a combination of download on the Milvan top (about 2,000 lb) due to fully developed rotor downwash 60 ft beneath the aircraft that was not properly accounted for in performance predictions, and to an underestimation of the amount of torque required for maneuvering vertically during dynamic stability testing in hover. The download was essentially eliminated with the short sling configuration, permitting hover and forward flight testing with the 15,000-lb load later in the test program.

Flight X-5 was aborted after only two data runs because of an engine malfunction, and these data were repeated on X-10.

5.4 TEST RESULTS

AAELSS II test results were recorded in the form of oscillograph time history data, or as a compilation of pilot comments and HQR taken at the time each data run was flown. Load pendular damping was assessed by applying the log-decrement method to determine the stability of the load "pendulum" angle decay characteristics with the AAELSS off, or with the system first off then on after load excitation. Some operational maneuvers were flown with the AAELSS engaged throughout, such as the precision placement, turn, and takeoff with offset load tasks. These tests were evaluated qualitatively with no damping assessments made.

The discussion of test results which follows is divided so that each sling and payload combination is highlighted separately. Ballasted Milvan/long riser hover testing is discussed first and is directly comparable to the ground test on the HLH cargo hoist tower described in Section 4.0.

TABLE 6

AAELSS II FLIGHT LOG

DECEMBER 9 TO 20, 1975 — EDWARDS AFB, USAAEFA

FLIGHT NO.	TAKEOFF GROSS WEIGHT	DATE	LOAD/SLING	PURPOSE	NO. DATA POINTS	FLIGHT TIME
X-1	34,128 Lb/Full	Dec 9 Tues	700/1,200 Lb Point Loads	Instrumentation Checks Functional Checkout Forward Flight Pulses AAELSS Retracted-Hook Jettison Tests Single-Point Loads	35	1 + 30
X-1A	34,128 Lb/Full	Dec 10 Wed.	700/1,200 Lb	AAELSS Damping Checks in Forward Flight Auto Jettison Single-Point Loads	17	1 + 45
X-2	Attempt 44,628 Lb 39,628 Lb/4,500	Dec 14 Sun.	Attempt At 15,000 Lb 10,000 Lb Long Riser	Hover 10,000 Lb Milvan 37' Riser Longitudinal AAELSS Only	9	1 + 15
X-3	41,428 Lb/4,500	Dec 15 Mon	11,800 Lb Short Sling	Loaded Milvan Hover - No Riser	31	1 + 15
X-4	36,928 Lb/Full	Dec 16 Tues	4,700 Lb Short Sling	Empty Milvan Hover - No Riser	40	1 + 30
X-5	41,428 Lb/4,500	Dec 16 Tues	11,800 Lb Long Riser Engine Chip Light Came On	Loaded Milvan Hover - 37' Riser	2	15 Min
X-6	41,428 Lb/4,500	Dec 17 Wed.	11,800 Lb Short Sling	Loaded Milvan Forward Flight 40, 65 Kn	31	1 + 30
X-7	41,978 Lb/5,050	Dec 19 Fri	11,800 Lb Short Sling	Loaded Milvan Forward Flight 80, 100 Kn	40	1 + 45
X-8	36,928 Lb/7,100	Dec 19 Fri	4,700 Lb Short Sling	Empty Milvan Forward Flight 40, 65, 80 Kn	50	2 + 05
X-9	42,400 Lb/2,300	Dec 20 Sat.	15,000 Lb Short Sling	Heavy Milvan Forward Flight 105 Kn Power Limit PIO and Dynamic Stability	12	25 Min
X-10	41,428 Lb/4,500	Dec 20 Sat.	11,800 Lb 37' Long Riser	Loaded Milvan Hover - Long Riser	21	50 Min

5.4.1 Long Riser/Heavy Payload - Hover

PENDULAR DAMPING - HLH tower tests preceding the flight program utilized a setup approximating conditions that would exist with the AAELSS installed on a perfectly stable hovering helicopter (at the start or finish of load winching operations). Several different control law shaping lag time constants were assessed at two different gain levels. In the flight program, similar lag shaping and gain variations were flown with 10,000 lb and 11,800 lb payloads. Flight and tower test results are compared against MILSPEC-H-8501A IFR requirements in Figure 38.

Damping for the longitudinal axis is depicted at the top of the plot, and lateral axis data is shown at the bottom. AAELSS-off basic sling load performance is indicated where the damping curves intersect the vertical axis. Note that inherent sling load damping is quite low (generally $\zeta << 0.05$). Unaugmented damping measured about the same for both axes, and was roughly half the MILSPEC IFR requirement. This lack of load damping is the primary cause of poor load placement characteristics in hover for most sling loads, especially those with long attachment risers.

Increasing lag time constant value improves damping up to a point. Very low time constants cause the arm to follow the load suspension cable, and the system operates like an underdamped elongated pendulum as described in Section 1.4.2. Long lags, on the other hand, tend to produce a rigid or nonmoving arm. Time constants somewhere between these extremes develop the desired arm damping performance as illustrated in the figure.

Generally, increasing gain level improves damping, but this occurs over a narrower band of arm travel and load swing prior to encountering actuator stall. The gains selected for the flight vehicle reflect the best compromise between damping and travel for both lateral and longitudinal axes. Note that gain setting is the ratio of commanded arm damping motion (in degrees) to the relative (pendulum) angle that the load suspension cable makes with the aircraft fuselage.

HARDWARE PROBLEM - Optimum lateral axis gain for the flight vehicle was half the maximum value tested on the tower. This gain was reduced to minimize effects of the hardware-associated forward arm long period oscillation described earlier. Gain reduction, and use of a lower washout time constant (from 13.5 sec down to 3.0 sec) in the lateral axis eliminated the lateral limit cycle in hover, but the problem continued to occur randomly in forward flight. The decreased washout did not appreciably reduce system damping.

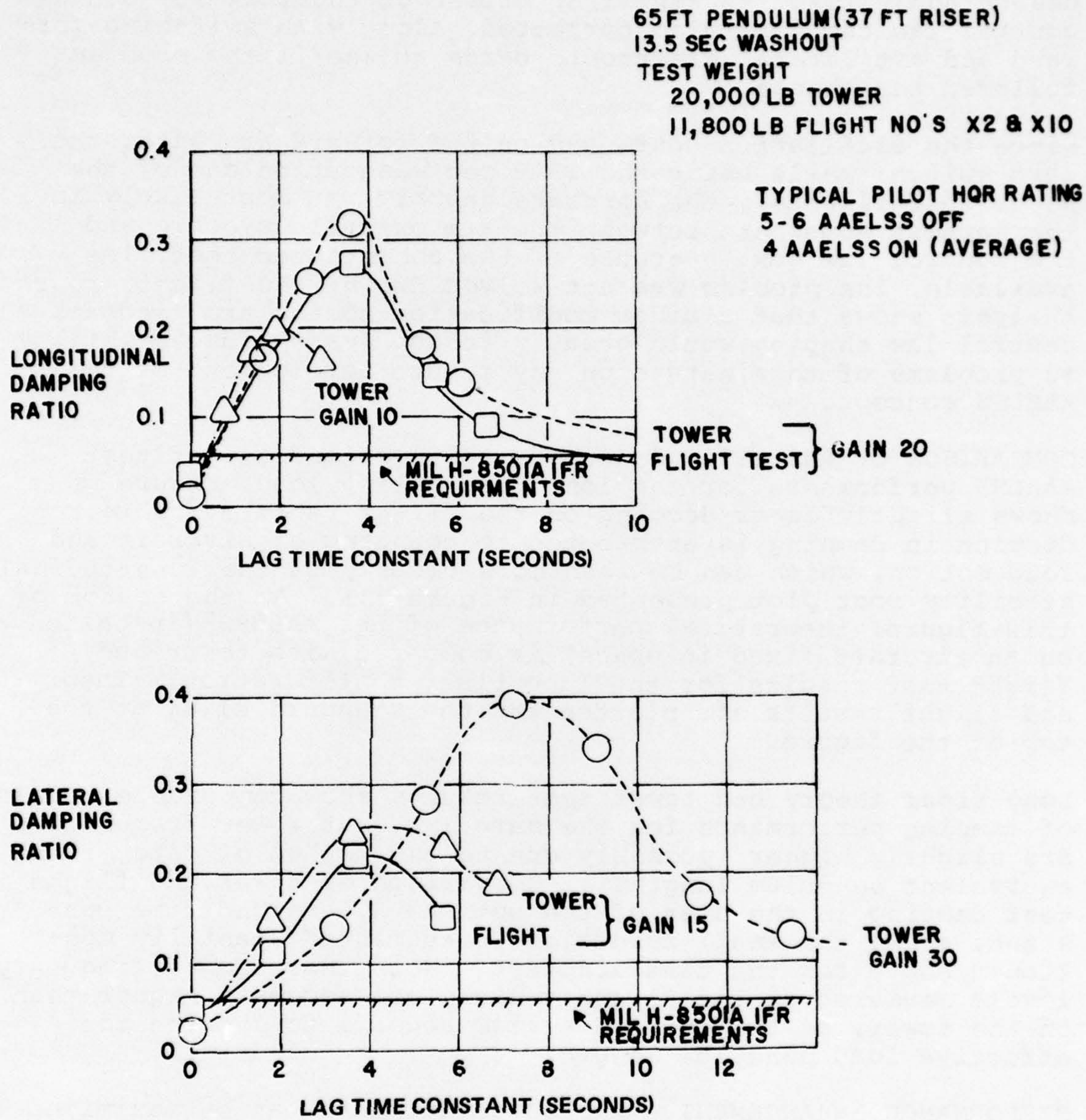


FIGURE 38. COMPARISON OF AAELSS II DAMPING IN HOVER TOWER VS FLIGHT TEST (LONG RISER)

In an attempt to solve the hardware problem, substantial effort was placed on balancing arm and cable angle feedback gain levels (the importance of which was pointed out in the Reference 2 design analysis). An amplifier offset on the forward lateral control law card was also corrected, along with switching forward and aft lateral electronic cards to see if the problem followed the change.

Since the oscillation continued on the forward arm after the card switch (while using the 13.5 sec washout on one of the hover test flights), the hardware anomaly was most likely in the harness somewhere between the arm or cable synchro and the control law box. Because of the abbreviated test time available, the problem was not solved during the flight program. Analysis shows that a minor modification to the arm feedback control law shaping would greatly reduce system susceptibility to problems of this nature on any future development of the AAELSS concept.

COMPARISON OF RESULTS - In comparing tower and flight test AAELSS performance for the long riser sling load, Figure 38 shows slightly lower damping on the flight vehicle. This reduction in damping is attributed to coupling of aircraft and load motion, which can be seen more clearly on the longitudinal stability root plot presented in Figure 39. At the bottom of this figure, theoretical performance of the AAELSS (installed on an aircraft fixed in space) is compared with tower and flight test results for the long riser configuration. Theory and flight results are plotted for the standard sling at the top of the figure.

Long riser theory and tower test results show comparable levels of damping performance for the same lag, but tower frequencies are slightly higher (possibly due to the method of determining equivalent pendulum lengths). Comparison of tower and flight test damping in the area of the optimum 3.6-second time constant, shows the small reduction in augmented stability mentioned above for the test aircraft. Note that damped frequency levels measured on the flight vehicle are somewhat higher than on the tower, as the coupled system appears to shorten the effective load pendulum length.

PERFORMANCE ENHANCEMENT - AAELSS performance can be maximized by decoupling the load from the airframe and by improving the stability of the aircraft on which the system is installed. Decoupling the load from the helicopter is most easily achieved by feeding back airframe attitude information for summation with the control law pendulum commands, so that the load is stabilized with respect to an inertial rather than aircraft coordinate system. Improved helicopter stability of the type required for high-precision load placement in hover has already been developed on the 347/HLH control system demonstrator

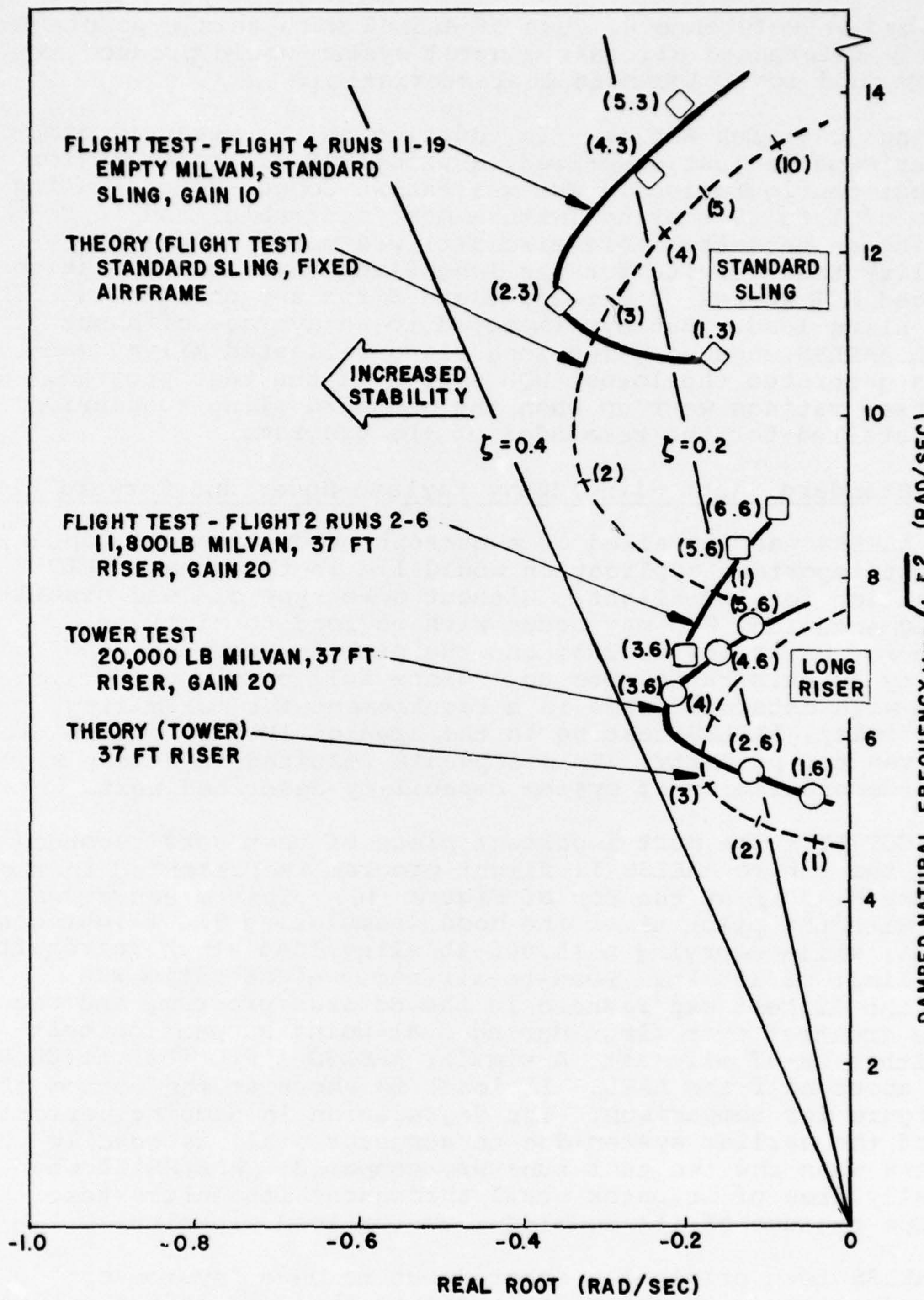


FIGURE 39. COMPARISON OF AAELSS II PREDICTED AND TEST MEASURED LONGITUDINAL DAMPING PERFORMANCE

described in Reference 6. Use of AAELSS with this type of velocity referenced aircraft control system would produce extremely good load placement characteristics.

Handling Qualities Rating - In addition to the measured damping performance just described, a pilot HQR was recorded for all test configurations. The well-known Cooper-Harper rating system of 1 to 10 scoring (with 1 most desirable, and 10 reflecting an uncontrollable aircraft) was used. Dynamic stability test results for the long sling hover configuration produced HQR scores of between 5 and 6 for the unaugmented basic sling load. Ratings improved to an average of about 4 with AAELSS engaged. The long sling-ballasted Milvan maneuvers generated the lowest HQR scores of the test program, but these ratings went up when the standard sling suspension was installed for the remainder of the program.

5.4.2 Standard Short Sling/Heavy Payload-Hover and Forward Flight

If an AAELSS was installed on a current production helicopter, its most important application would lie in the area of PIO elimination for IMC flight. Without some type of load stability augmentation, PIO may occur with payload to airframe weight ratios as low as 25%, and the problem increases in severity as this ratio goes up. Since full envelope IMC flight with external loads is a requirement for maximizing productivity, AAELSS testing in the area of IMC/PIO elimination was given top priority. This emphasis resulted in a very significant demonstration of system capability described next.

PIO RECOVERY - The most important piece of test data recorded during the entire AAELSS II flight program is presented in the PIO time history at the top of Figure 40. This maneuver was flown with the pilot under the hood (simulating IMC flight conditions) while carrying a 15,000-lb sling load at the aircraft power limit of 105 kn. Load-to-airframe weight ratio was 0.55, the highest experienced in the Edwards program, and one of the greatest ever flown during dual-point suspension testing with a CH-47 aircraft. A similar AAELSS I PIO test at 80 kn (with about half the AAELSS II load) is shown at the bottom of the figure for comparison. The degradation in damping performance of the earlier system due to actuator stall is readily apparent when the two test runs are compared. AAELSS II was virtually free of actuator stall throughout its entire test envelope because of its doubled actuator load capacity.

The AAELSS test originally started out to be a "system off" PIO evaluation, with the pilot exciting the load at its natural frequency by slowly moving the longitudinal stick back and forth in a sinusoidal pattern. Longitudinal load motion gradually built up as the pilot manipulated the controls in response to perceived acceleration cues measuring as high as

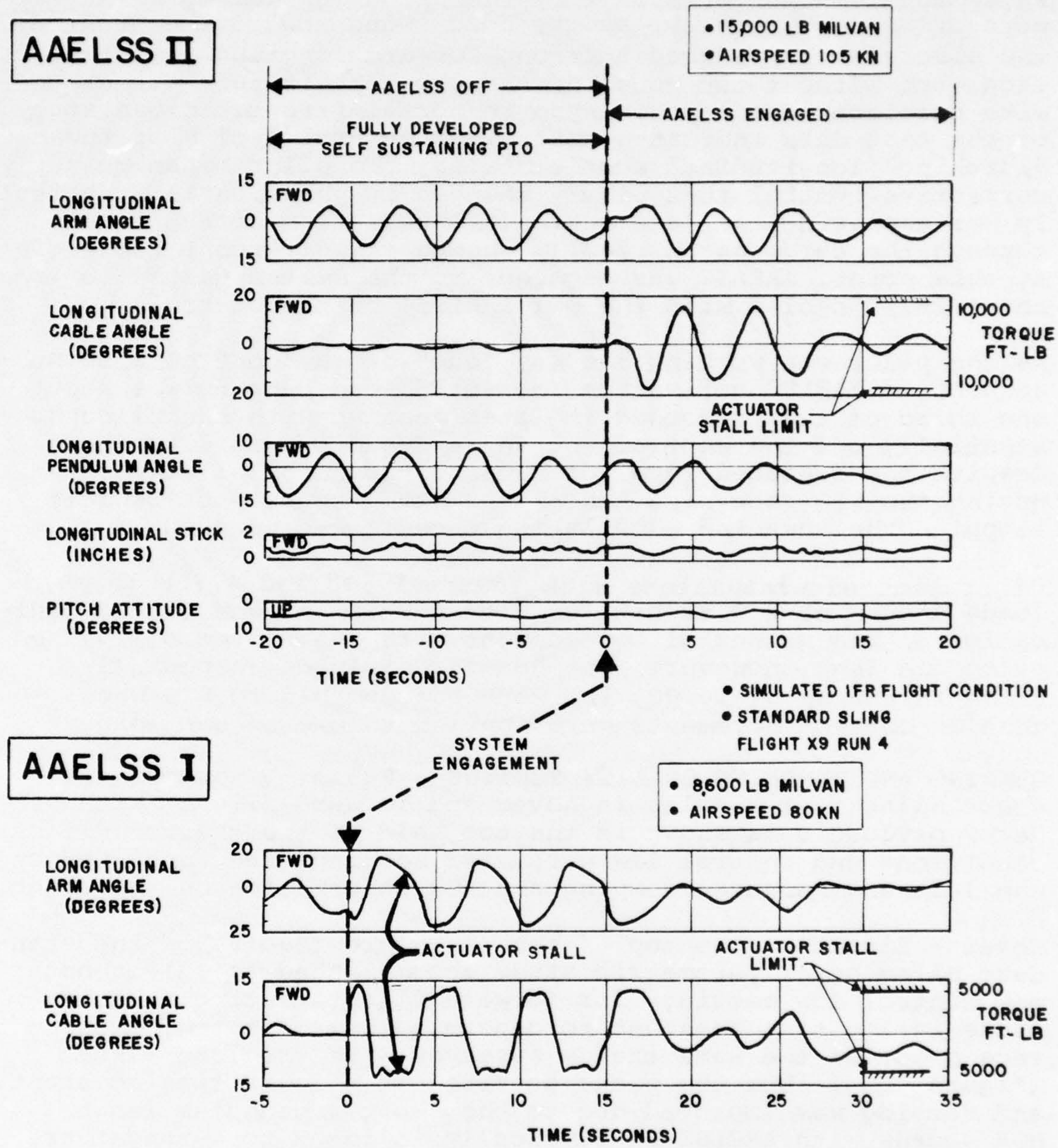


FIGURE 40. RECOVERY FROM LONGITUDINAL PILOT-INDUCED OSCILLATION BY ENGAGING AAELSS SYSTEM

$\pm 0.1g$ along the aircraft longitudinal axis. After about 4 to 5 cycles, a fully developed case of PIO existed with the pilot unable to attenuate load swing amplitude by further control inputs.

False acceleration cues felt by the pilot (and crew) were very perceptible. Typically, as the load swung toward the front of the aircraft it produced a strong forward longitudinal acceleration, but without the usual nosedown pitch attitude associated with accelerations of this type in normal flight. Close study of the test data indicates that after several cycles of these "lurching" longitudinal accelerations, the pilot began to apply corrective control that slowly changed in phase until it actually was assisting the load motion. Observation of the load through the cargo hatch clearly showed its divergent tendencies. At this point, AAELSS was engaged and the system damped out in about 2-1/2 cycles with the pilot still on the controls.

As the pilot was working his way "out" of the control loop subsequent to AAELSS activation, measured load damping was about one third of that recorded in later testing with the pilot substantially off the controls during a dynamic-stability run. Despite the degraded level of damping caused by pilot inputs during the PIO recovery, AAELSS was still capable of rapidly stopping the unwanted oscillation once it was engaged.

Other limited evaluations with lower 11,800 and 4,700 lb payloads showed no PIO tendencies with AAELSS on, and little indication of its potential development with the system off. The pilot did feel, however, that heavier payloads (especially those in excess of 10,000 lb) were susceptible to PIO when gust or control movements were applied to excite the load.

DAMPING AND HANDLING QUALITY TESTING - Table 7 summarizes short sling test results in hover and forward flight with heavy payload data shown in the top half of the chart. Flight conditions and control law parameter settings are annotated on the left and measured damping and HQR information on the right.

Hover - Listed at the top of the table are results of the standard sling hover parametric study accomplished to select optimum control law settings for forward flight testing. Variations in lag time constant to determine best damping performance produced the same trends observed with the long riser (Figure 38), but the peaks occurred at a lower time constant, and damping was improved due to the shorter pendulum length. HQR scores with AAELSS on (typically in the 3 to 4 range) are somewhat better for the short standard sling configuration because of its higher inherent stability.

An example of longitudinal axis time history data taken in hover with AAELSS off, and with the system off, then on, after aircraft excitation, is presented in Figures 41 and 42.

TABLE 7

STANDARD SLING DAMPING AND HANDLING QUALITIES SUMMARY - AAELSS ON AND OFF

FLIGHT CONDITION AIRSPEED (KNOTS)	AAELSS CONDITION OFF	AAELSS CONDITION ON	AAELSS CONTROL LAW SHAPING TIME CONSTANTS LAG (SEC)	WASHOUT (SEC)	MEASURED DAMPING RATIO PERCENT OF CRITICAL LONG AXIS	LATERAL AXIS	PILOT HANDLING QUALITIES RATING LONG AXIS	LATERAL AXIS
Std Sling	11,800 Lb Milvan							
Hover	X			15 Long 13 Latl	0.08	0.12	5-6	5-6
		X	1.3		0.11	0.35	-	4
OPTIMUM		X	2.3		0.25	0.30	3-4	3-4
		X	3.3		0.22	0.28	4	4
		X	5.3		0.16	0.16	4	5
40	X						4-5	6
		X	2.3	6.5 Latl			-	
65	X				0.044	0.11	5-6	5
		X			0.35	0.30	3-4	3-4
		X			0.22 (Pilot in loop)		-	-
80	X				0.08	0.15	4	4
		X			0.28	0.39	3	3
100	X				0.03	0.22	4	4
		X			0.30	0.30	-	-
Std Sling	15,000 Lb Milvan							
105	X				0.07	0.08	5	4
		X			0.28	0.30	3	3
PIO CASE	X				Unstable		6-8	*Tends Toward Uncontrollable*
		X			0.10 (Pilot in loop)		3	
Std Sling	4,700 Lb Empty Milvan							
Hover	X				0.05	0.08	5	5
		X	1.3	6.5 Latl	0.15	0.28	5	5
OPTIMUM		X	2.3		0.30	0.30	3-4	3-4
		X	3.3		0.18	0.22	3-4	3-4
		X	5.6		0.15	---	4	
		X	2.3	3.0 Latl		0.36		-
65	X				0.05	0.07	4	5
		X			0.25	0.35	3	3
80	X				0.12	0.11	4	4
		X			0.31	0.30	3	3
Std Sling	Single Arm Operating	11,800 Lb Milvan						
Hover	Longitudinal Rear Arm On				0.11	0.20		
100	Lateral Front Arm On				0.25	0.25		
		4,700 Lb Empty Milvan						
Hover	Longitudinal Rear Arm On				0.16	0.08		
80	Lateral Front Arm On				0.22	0.30		

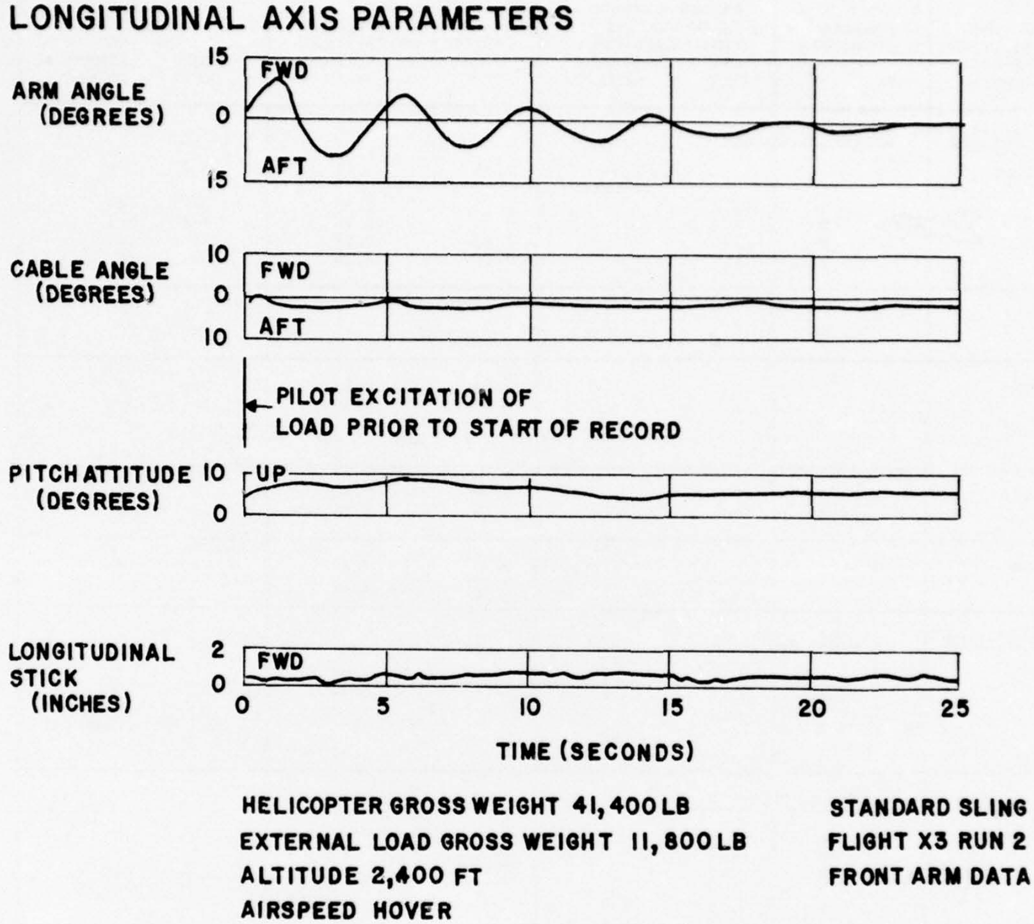


FIGURE 41. LONGITUDINAL DYNAMIC STABILITY IN HOVER – BALLASTED MILVAN – AAELSS OFF

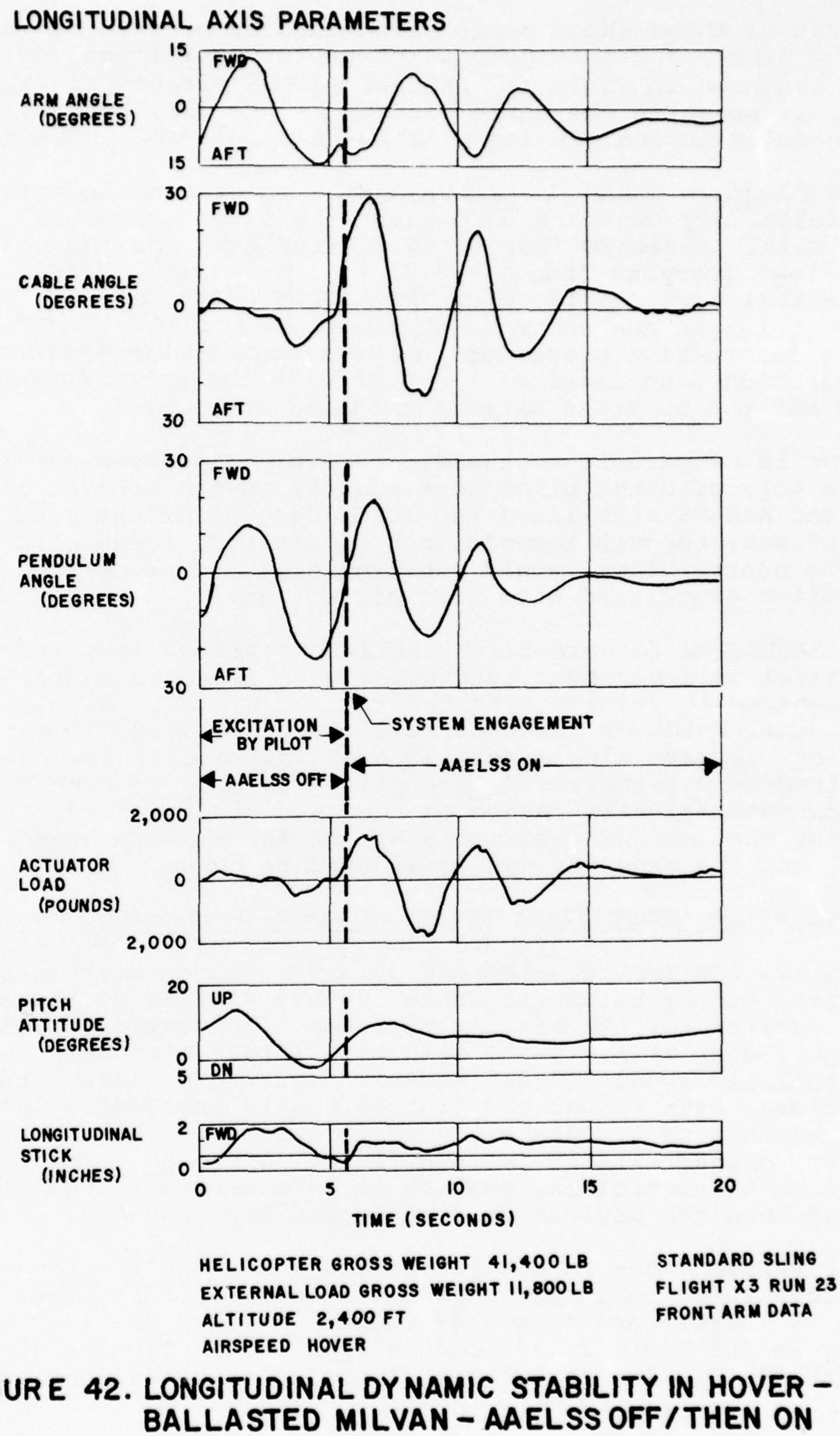


FIGURE 42. LONGITUDINAL DYNAMIC STABILITY IN HOVER – BALLASTED MILVAN – AAELSS OFF/THEN ON

The first of these shows basic sling load damping to be very low (ζ = 0.08), and this does not improve significantly with speed, as shown in Table 7. Lateral AAELSS off damping is higher, as shown in the table (and in Figure 32), because the load pendulum motion couples with the aircraft roll mode.

Forward Flight - Table 7 - shows AAELSS on damping in both axes to be relatively constant throughout the flight envelope, and approximately three to four times greater than for the unaugmented load (varying from ζ = 0.25 to ζ = 0.39). Typical longitudinal test results with the AAELSS off and on in forward flight at 105 kn are shown in Figures 43 and 44. Time history information presented in the second figure indicates a measured damping level of ζ = 0.28 with the pilot substantially off the controls after the AAELSS engagement.

This run is comparable to the PIO recovery discussed earlier (Figure 40), with the pilot continuously in the control loop while the AAELSS stabilized the load. Decoupling the load from the airframe, through introduction of attitude feedback data into the control laws, would substantially reduce damping degradation associated with aircraft motion.

In the AAELSS II forward flight buildup testing, longitudinal and lateral axis hardover recoveries were found to be rather mild compared to results with the earlier system. Simulated longitudinal hardover failures were almost imperceptible to the pilot, as were single-axis lateral failures at low speed. When airspeed was increased, the pilot was able to discern some small directional trim change of the load after lateral failures, but the load did not oscillate at the maximum speeds tested, and the maneuver was considered to be very gentle.

5.4.3 Standard Short Sling/Empty Milvan - Hover and Forward Flight

DAMPING AND HQR TESTING - AAELSS on/empty Milvan test results summarized at the bottom of Table 7 are similar to those discussed earlier for the heavier payloads. Augmented pendular damping is approximately the same at all test airspeeds and is essentially equal to that measured for the ballasted configurations, even though the lighter box is inherently less stable because of its weaker "gravity spring". This constant stability characteristic is significant, since no complicated variations in control law shaping or parameter settings are required when the payload or flight condition changes.

Damping values shown in the table were measured from time history plots like those shown for the lateral axis in Figures 45 and 46 (hover) and 47 and 48 (80 kn cruise). The lack of damping in the basic sling load is apparent in Figures 45 and 47, with $\zeta \approx 0.1$ for both cases. Despite this low inherent

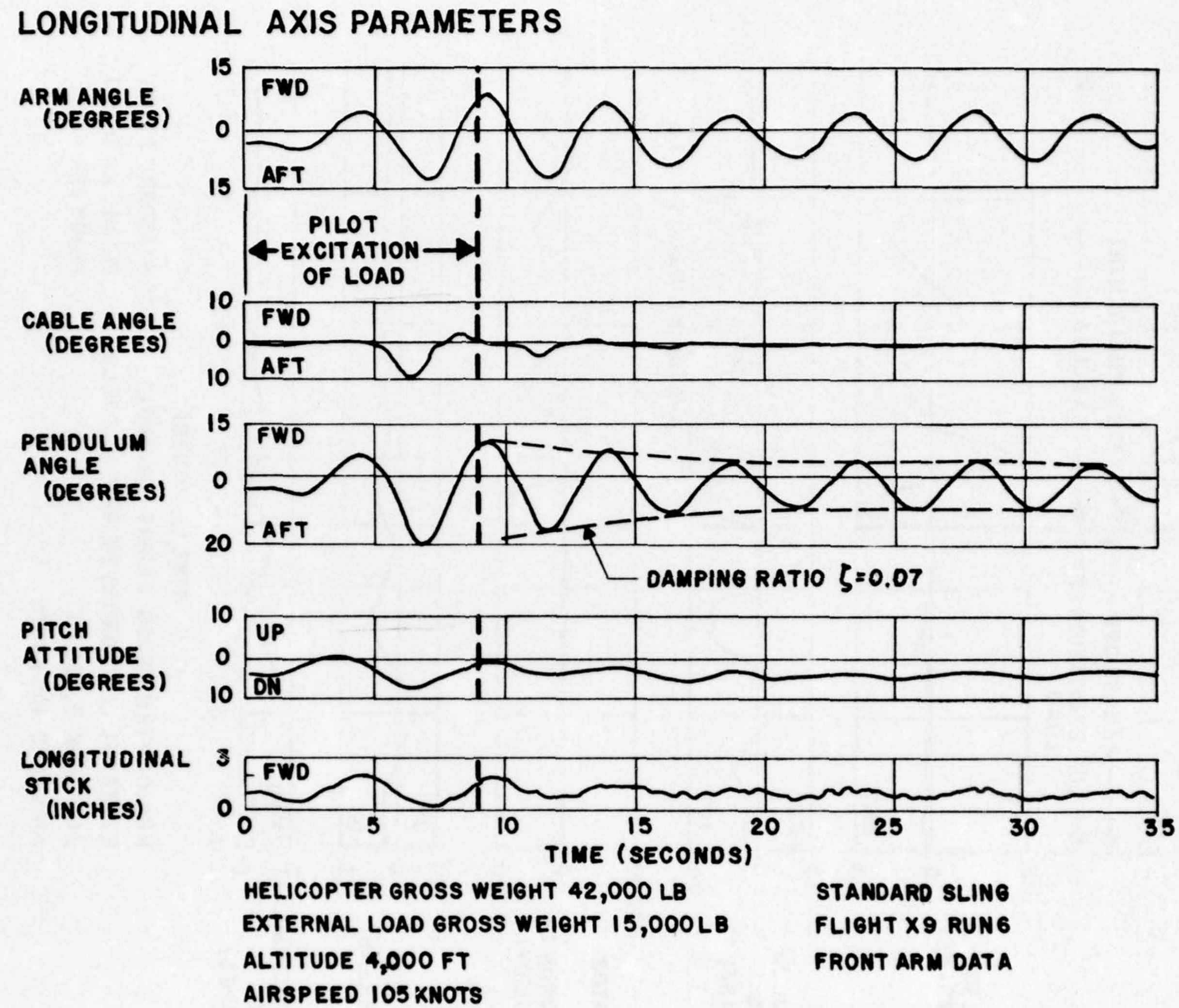


FIGURE 43. LONGITUDINAL DYNAMIC STABILITY AT 105 KNOTS – LOADED MILVAN – AAELSS OFF

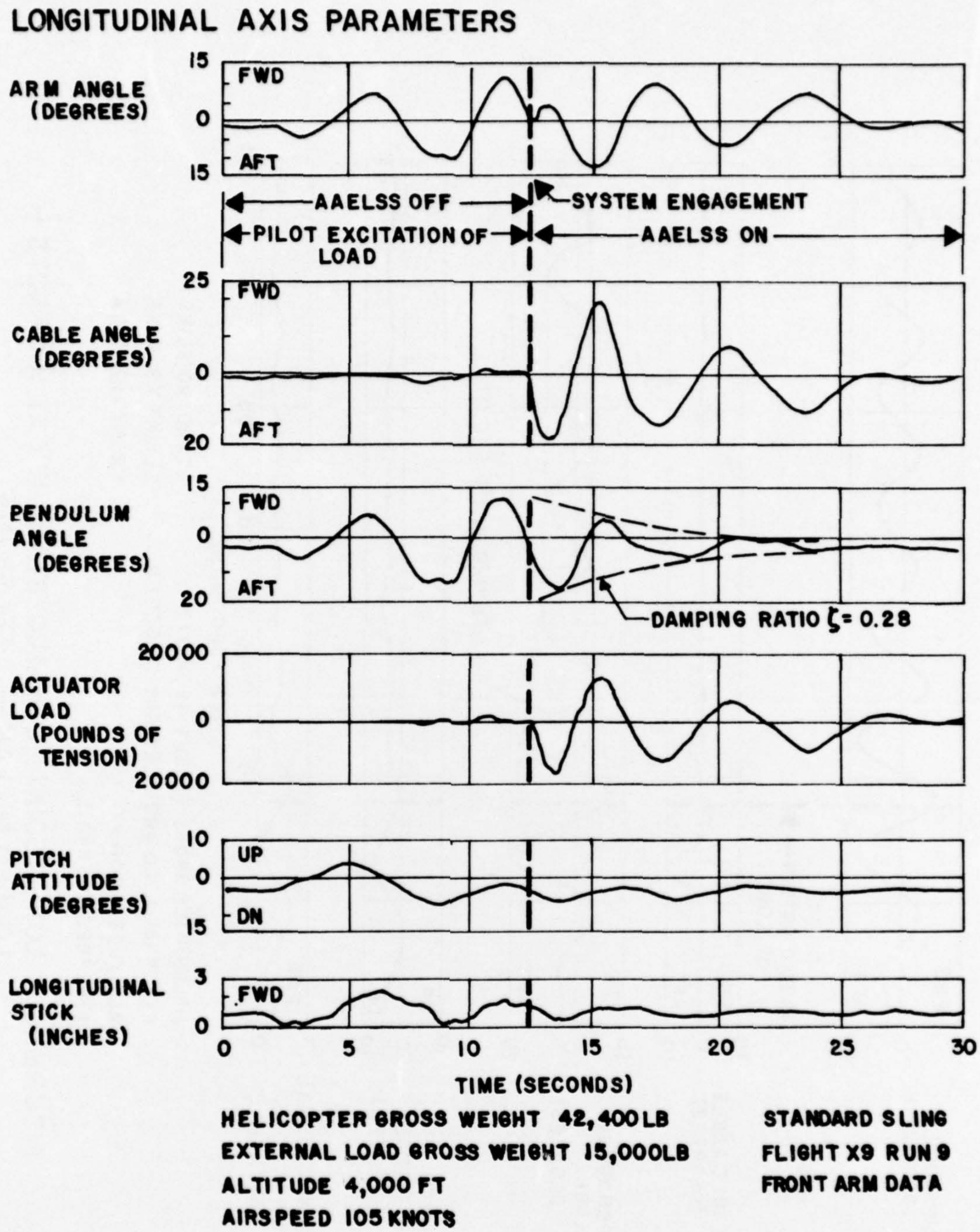


FIGURE 44. LONGITUDINAL DYNAMIC STABILITY AT 105 KNOTS – LOADED MILVAN – AAELSS ON

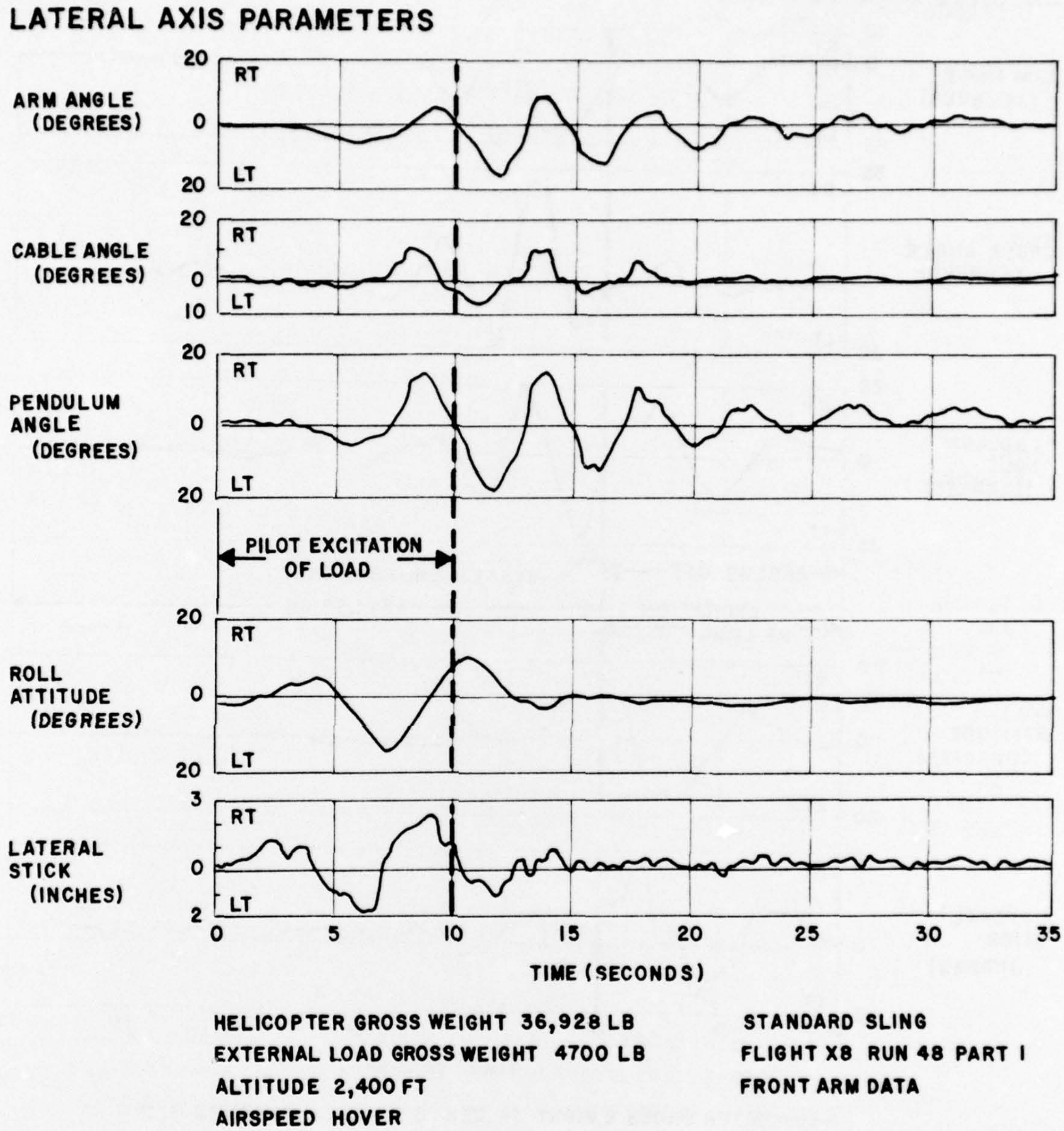


FIGURE 45. LATERAL DYNAMIC STABILITY IN HOVER – EMPTY MILVAN – AAELSS OFF

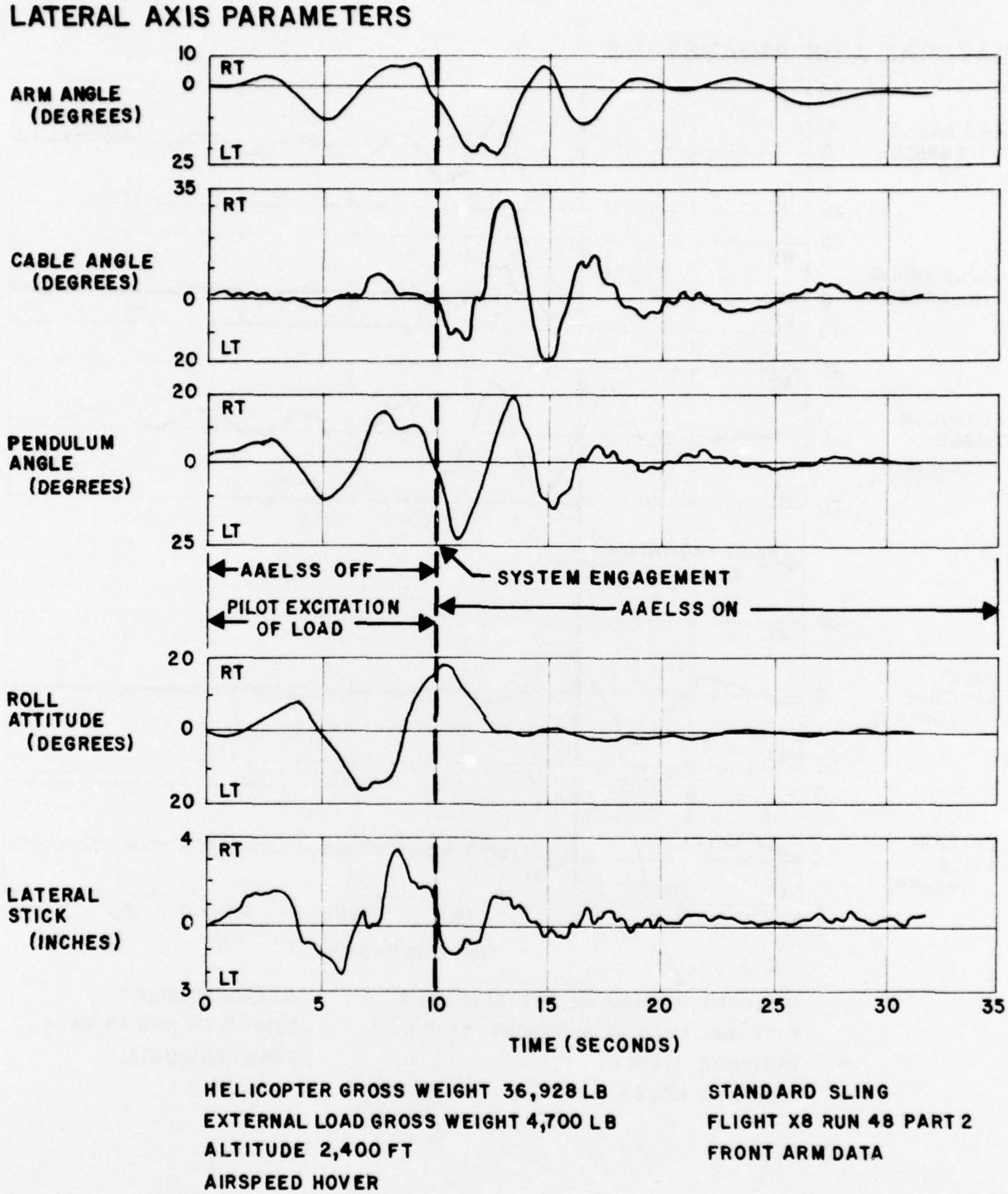


FIGURE 46. LATERAL DYNAMIC STABILITY IN HOVER — EMPTY MILVAN — AAELSS OFF/THEN ON

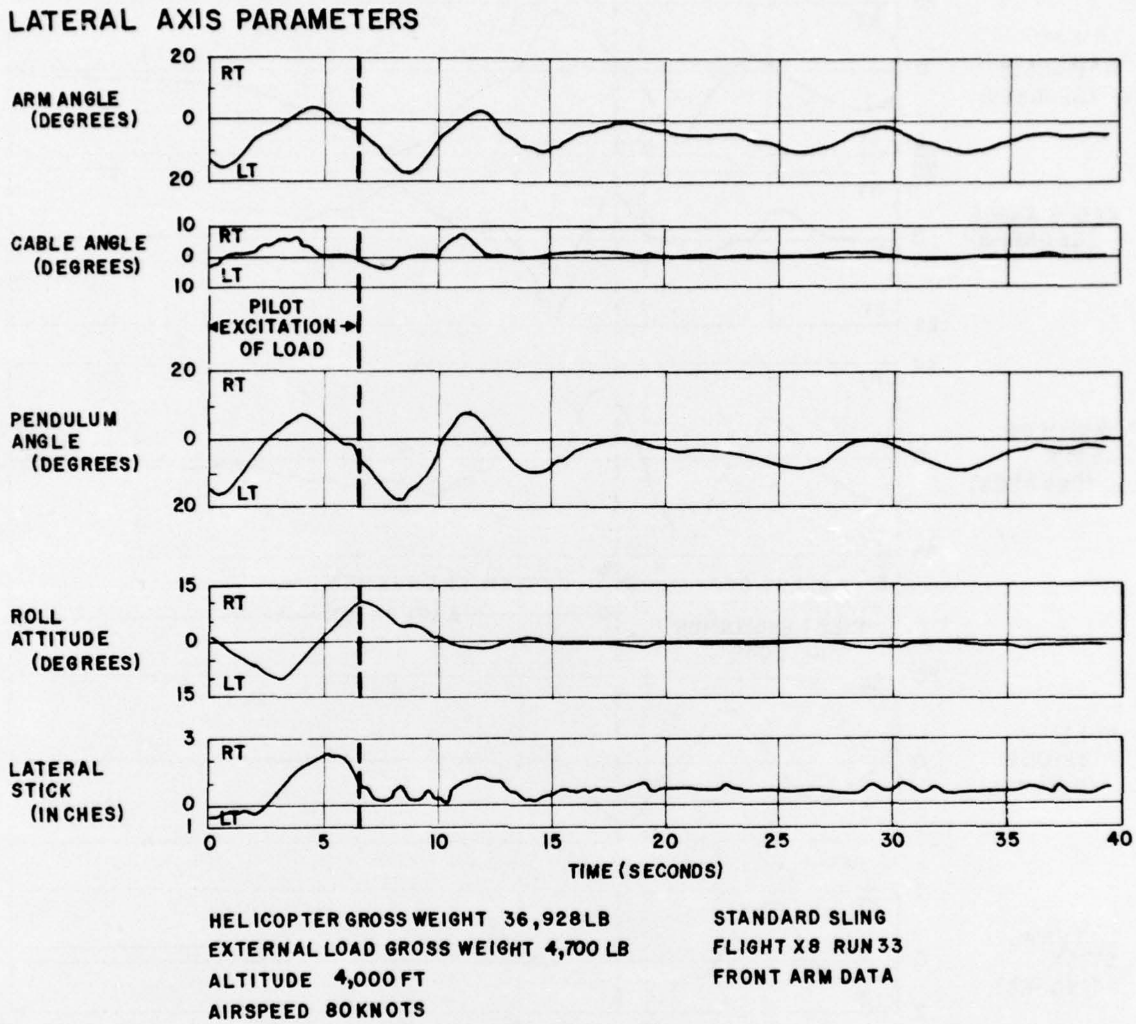
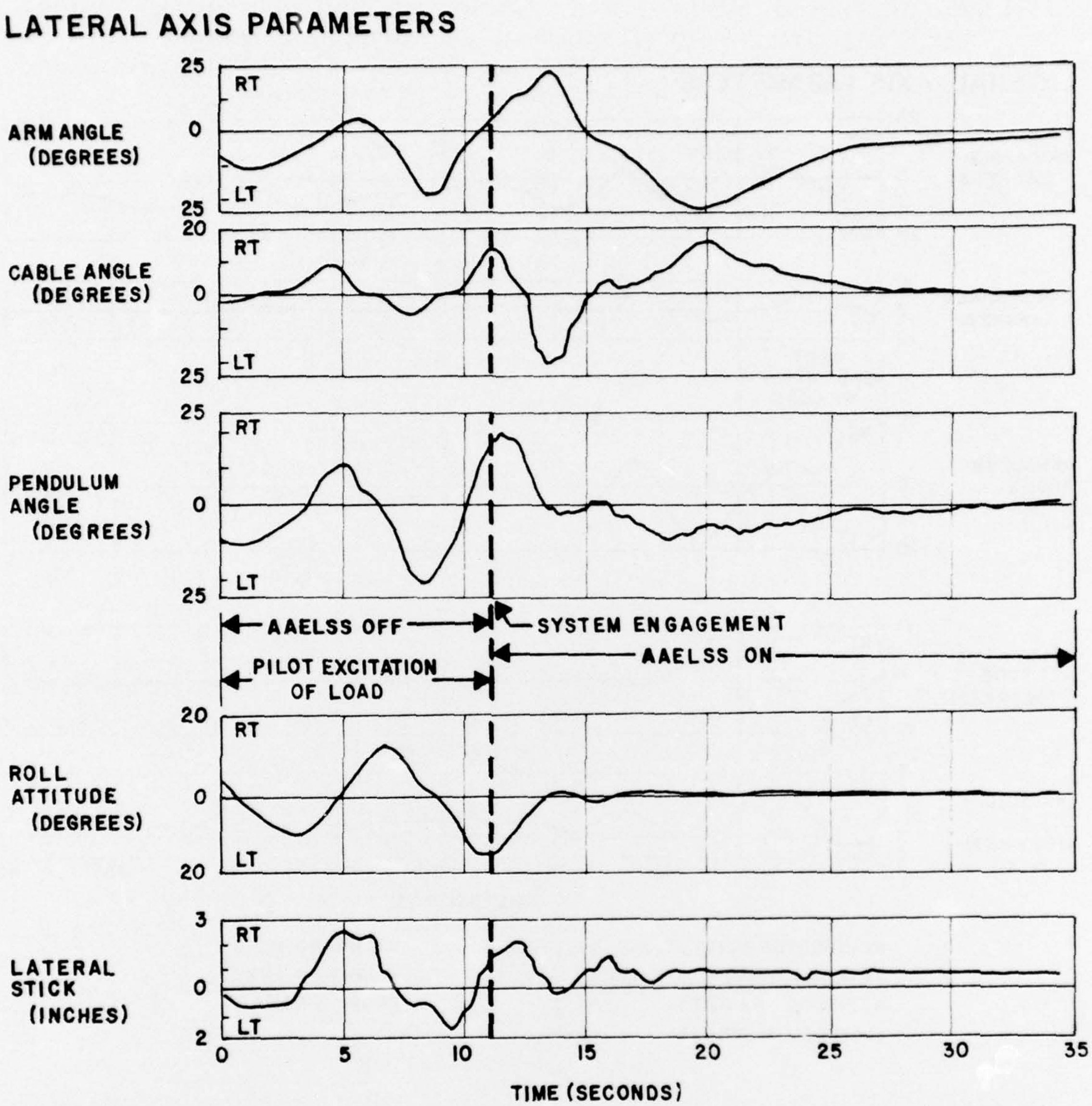


FIGURE 47. LATERAL DYNAMIC STABILITY AT 80 KNOTS – EMPTY MILVAN – AAELSS OFF



HELICOPTER GROSS WEIGHT 36,928 LB
EXTERNAL LOAD GROSS WEIGHT 4,700 LB
ALTITUDE 4,000 FT
AIRSPEED 80 KNOTS

STANDARD SLING
FLIGHT X8 RUN 42
FRONT ARM DATA

FIGURE 48. LATERAL DYNAMIC STABILITY AT 80 KNOTS – EMPTY MILVAN – AAELSS OFF/THEN ON

pendular damping, unaugmented stability levels are approximately equal to the MIL SPEC H-8501A IFR requirement (with $\zeta \geq 0.11$ for the short sling configuration). Meeting the MIL SPEC requirements, however, does not necessarily ensure adequate handling qualities for cruising with external loads or attempting precision placement in hover, in view of the obviously poor HQR scores (mostly in the 5 to 6 range) recorded with the basic sling load for these flight modes.

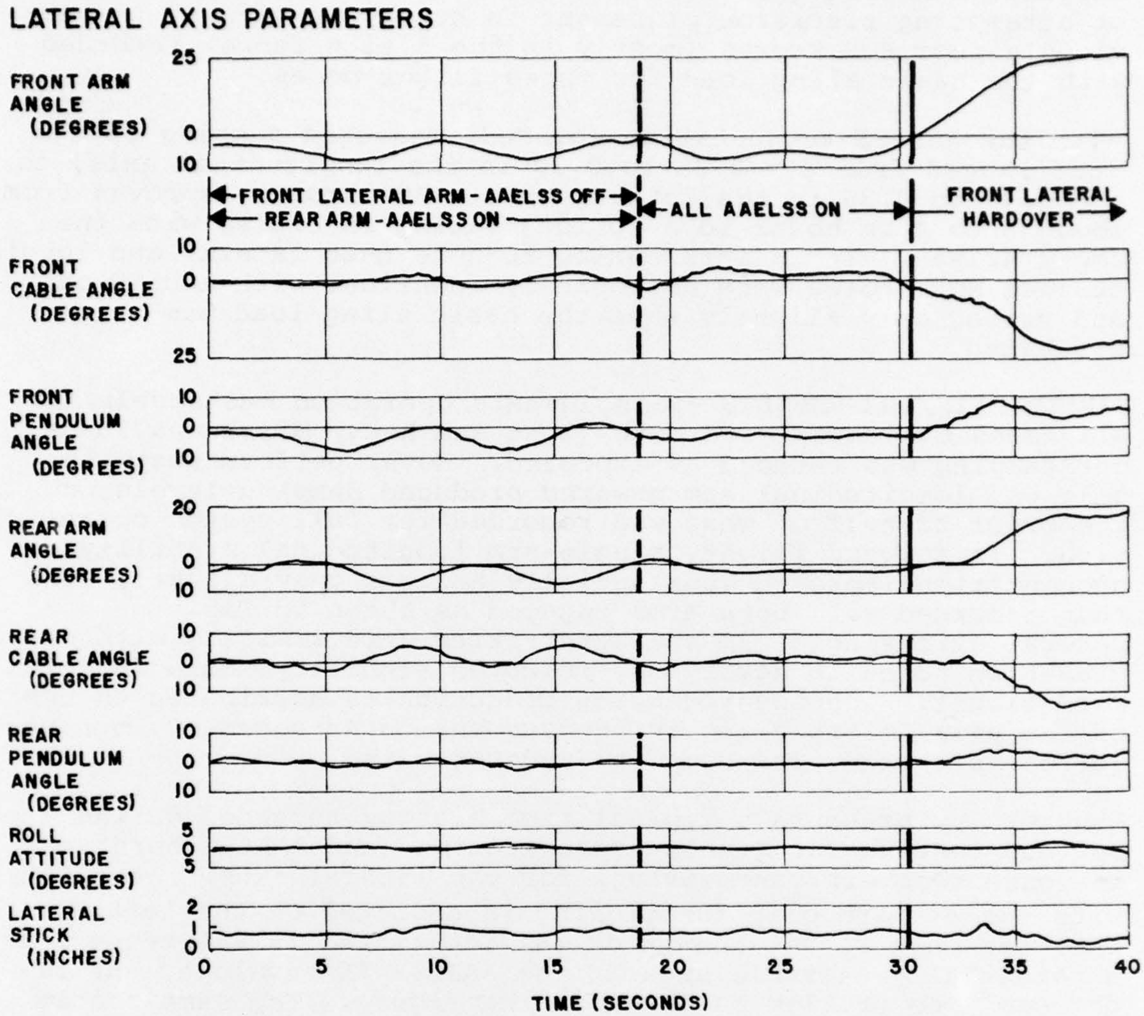
With the AAELSS augmentation engaged, measured damping of the load ranged from $\zeta = 0.25$ to 0.30 in the longitudinal axis, to $\zeta = 0.30$ to 0.35 in the lateral axis. HQR scores improved from about 3 to 4 in hover to a solid 3 rating in cruise with the empty Milvan. It is interesting to note that lateral and longitudinal HQR scores were essentially identical with AAELSS on, and varied only slightly when the basic sling load was being evaluated.

SINGLE-AXIS/ARM RESULTS - Single-axis operation was stable for all cases evaluated with both light and heavy Milvan payloads, but damping was reduced as expected. Hover performance with only one longitudinal arm powered produced damping levels on the order of half of what was recorded for full system operation. In forward flight, single-arm longitudinal stability augmentation improved substantially and was only slightly less than recorded with both arms engaged as shown in Table 7. Lateral axis single-arm characteristics were similar, with degradation noted in hover, and improved stability found in forward flight. The hover damping reduction is attributed to use of the paralleling sling in the suspension arrangement, but requires more study for complete understanding.

Figure 49 presents a typical time history recorded during buildup testing for single-arm operation (and AAELSS hardover response recovery maneuvering) for the lateral axis. Stability with the aft arm only functioning is depicted on the left. This aft-only flight condition was identified in Reference 2 as a potentially unstable area in the AAELSS II envelope, but is obviously no problem as shown in the figure. The same stable characteristics were also found at higher speeds and with the heavier payloads.

HARDOVER TESTING - The single lateral axis test was normally followed by a period of operation with the entire system engaged, as shown in the center of Figure 49. In this configuration, the forward arm was failed hardover to evaluate load response with the aft arm still providing stability inputs. The Milvan yawed initially in the direction of the failure and then slowly damped out to a trim sideslip angle.

As indicated earlier, the pilot felt the hardover response to be relatively mild. In fact, on several occasions the hard-



HELICOPTER GROSS WEIGHT 36,928 LB

EXTERNAL LOAD GROSS WEIGHT 4,700 LB

ALTITUDE 4,000 FT

AIRSPEED 65 KNOTS

STANDARD SLING

FLIGHT X8 RUN 25

FIGURE 49. AAELSS OPERATION WITH FRONT ARM LATERAL AXIS OFF, THEN ON, THEN FAILED HARDOVER - ALL OTHER AXES ENGAGED

over input went undetected by the pilot, prompting a comment that some indication of system failure or hardover status should be provided in the cockpit as a safety feature. This could be accomplished through use of warning lights.

SYSTEM SIMPLIFICATION - On the basis of the generally favorable forward flight performance with single-arm and/or axis AAELSS operation, some potential exists for mechanizing a simplified single forward arm system to meet the PIO associated IMC requirements stated in Section 1.2. The single-arm approach would be applicable for missions where no requirement exists for precision load placement or flight with unstable loads.

A second simplification possible for the same type of mission would utilize only longitudinal axis AAELSS units, with the lateral actuators eliminated completely. This type of system would have better hover performance and would possess redundant capability in the event of failures, but would be less effective in forward flight because of no lateral augmentation. The advantage of either approach toward system simplification lies in the potential for substantial weight and cost reduction for the overall installation.

5.4.4 Comparison of AAELSS II and AAELSS I Performance

Figure 50 compares damping performance measured with the original and most recent AAELSS mechanizations. Triangular data points represent AAELSS II damping levels, and the circles apply to the AAELSS I results. As is clearly demonstrated in the chart, AAELSS II is superior to the initial system in most areas tested.

On the left, open data points show the AAELSS II suspension for the heavy payload to be substantially more stable in the lateral axis for all airspeeds evaluated. This improvement primarily results from the use of a shorter arm and riser combination in AAELSS II (10 ft vs 14.5 ft). The reduction in inverted "Y" riser length also "stiffens" the yaw axis appreciably, eliminating the tendency toward directional axis limit cycling noted with the earlier system.

Data shown in the center of the chart for the long riser configuration again demonstrates AAELSS II superiority. With the system off, inherent damping was about the same for both payloads; but a substantial performance advantage was demonstrated with the newer AAELSS engaged, even though the payload being stabilized was about three times as great as with the earlier device. Augmented damping for the empty Milvan payloads shown on the right side of Figure 50 was essentially the same for both systems.

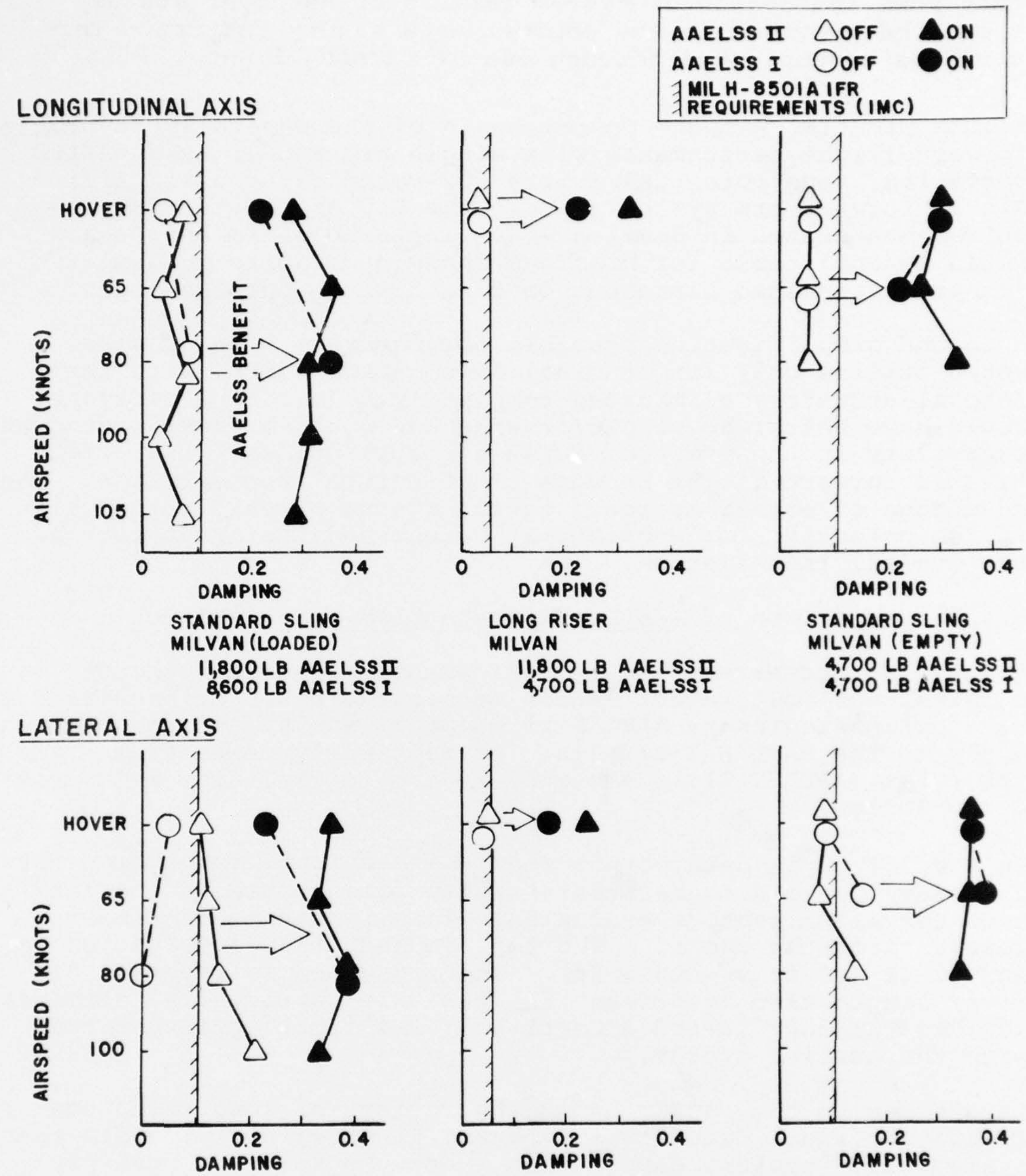


FIGURE 50. COMPARISON OF AAELSS II AND AAELSS I PENDULAR DAMPING PERFORMANCE

5.4.5 Operational Maneuvers

Although most operational maneuvers were not formally rated during the test program, the pilots did feel that AAELSS stability augmentation provided improved external load handling qualities for virtually all evaluation maneuvers flown. In the precision load placement task, the pilot commented that the system helped him "put the load where he wanted it to go," and noted an HQR improvement of about 1 point with the system engaged for the long riser configuration.

The AAELSS performed well in steady banked 10 and 20 degree level flight turns, and was given an HQR score of 3 in straight and level flight with the 15,000 lb Milvan payload. Takeoff maneuvers with offset loads and partial power descents while maneuvering to land were accomplished with no problems using the AAELSS.

6.0 CONCLUSIONS

1. The Edwards AFB AAELSS II evaluation established the feasibility of using a system of this type to stabilize external loads on tandem rotor and HLH-type aircraft with winchable cargo hoist systems. All pretest objectives were met in the USAAEFA program.

   With modification, the active arm concept is applicable to single rotor aircraft as well.

2. The AAELSS effectively eliminates any tendency for an external load to cause longitudinal PIO in IMC flight. Should PIO develop with the system disengaged, it can be eliminated quickly by activation of the system.

3. The AAELSS II demonstrated load damping levels in the range of $\zeta = 0.25$ to 0.39, which either duplicated or exceeded the AAELSS I performance, and doubled the payloads flown with the original system. Pilot workload was reduced appreciably with the AAELSS engaged, and this resulted in improved HQR ratings throughout.

4. Stall torque sizing of the AAELSS II hydraulic cylinders (more than twice AAELSS I capacity) eliminated the actuator stall problem identified with the original system. With this substantially increased performance, the system still did not impose excessive electrical or hydraulic power requirements on test vehicle subsystems.

   In the flight demonstration program, no unsafe condition was caused by AAELSS operation, or by any simulated failure modes of the system.

5. Rotor and control system loads were monitored during the test program with a cruise guide indicating system. The highest observed reading was on the order of 55% while maneuvering with the heaviest load. On the basis of these results, it is apparent that the AAELSS did not adversely affect operation of the aircraft from the standpoint of its structural envelope.

6. Improved arm and cable angle sensing eliminated the low amplitude limit cycle tendency (at the load natural frequency) identified with AAELSS I sensor hysteresis.

7. Damping performance measured throughout the test envelope for all payloads evaluated was relatively constant with the system engaged. As a result of

this, no complicated changes in control law shaping or parameter sizing are required when the flight condition or payload is changed.

If AAELSS were employed with a winchable cargo hoist system, a simple gain and time constant change (to account for longer sling lengths) could be made by the pilot through use of a manual mode change switch while winching operations were in progress.

8. Potential exists for mechanizing a simplified, lighter, and less costly AAELSS concept using a single forward arm or a set of dual arms with no lateral actuators to eliminate PIO in IMC flight. The simplified system would have application for missions where no requirement was imposed for precision load placement in hover or flight with unstable loads.

9. Improvements in AAELSS operation are possible by modifying the control law package to decouple load/airframe response modes through use of attitude feedbacks to cancel aircraft motion effects. Other improvements in control law feedback shaping have been shown (by preliminary analysis) to reduce system susceptibility to hardware problems such as the lateral long period oscillation. Both of these control law changes should be investigated through further analytical development of the concept.

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